NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

OTTER: AN OPTIMIZED TRANSIT TOOL AND EASY REFERENCE

by

Warren Korban Blackburn

March 2016

Thesis Advisor:	Emily Craparo
Co-Advisor:	Connor McLemore
Second Reader:	Dan Nussbaum

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704–0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** March 2016	**3. REPORT TYPE AND DATES COVERED** Master's thesis	
4. TITLE AND SUBTITLE OTTER: AN OPTIMIZED TRANSIT TOOL AND EASY REFERENCE			**5. FUNDING NUMBERS**
6. AUTHOR(S) Warren Korban Blackburn			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

Fuel efficiency is a priority for the Chief of Naval Operations (CNO), as stated in the *CNO's Position Report: 2014*. While a number of fuel-saving measures have been implemented in recent years, the effects of operational transit speed on fuel consumption have not been adequately understood as a variable.

Ships' commanding officers use fuel-usage curves to determine the most efficient propulsion-plant speed. Fuel efficiency is typically gauged by maintaining a consistent optimal speed. Often there are combinations of speeds that are more efficient than a constant speed. The transit fuel planner, developed in the Naval Postgraduate School's operations research department by Brown, Kline, Rosenthal, and Washburn in 2007, calculates speed combinations to achieve fuel savings for a given single ship. This thesis adds additional capacities based upon common principles.

We provide an omnibus tool, the Optimized Transit Tool and Easy Reference (OTTER), with two complementary components: Dynamic OTTER and Static OTTER. Dynamic OTTER is a versatile, interactive transit-planning tool for any ship class that accommodates drill scheduling, a critical feature. The second tool, Static OTTER, is a generic, optimal solution to individual ship transit-speed combinations, in the form of a printable reference sheet that can be used independently. These products are being implemented by United States Navy surface ships and will yield significant fuel savings, equating to additional time on station.

14. SUBJECT TERMS OTTER, fuel optimization, transit fuel planner, fuel savings, fuel consumption, replenishment at sea planner surface fleet, surface action group planner			**15. NUMBER OF PAGES** 107
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540–01-280-5500 Standard Form 298 (Rev. 2–89) Prescribed by ANSI Std. 239–18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

OTTER: AN OPTIMIZED TRANSIT TOOL AND EASY REFERENCE

Warren Korban Blackburn
Lieutenant Commander, United States Navy
B.A., Thomas Edison State College, 2003
B.S.A.S.T., Thomas Edison State College, 2004

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
March 2016

Approved by: Emily Craparo
Thesis Advisor

Connor McLemore
Co-Advisor

Dan Nussbaum
Second Reader

Patricia Jacobs
Chair, Department of Operations Research

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Fuel efficiency is a priority for the Chief of Naval Operations (CNO), as stated in the *CNO's Position Report: 2014*. While a number of fuel-saving measures have been implemented in recent years, the effects of operational transit speed on fuel consumption have not been adequately understood as a variable.

Ships' commanding officers use fuel-usage curves to determine the most efficient propulsion-plant speed. Fuel efficiency is typically gauged by maintaining a consistent optimal speed. Often there are combinations of speeds that are more efficient than a constant speed. The transit fuel planner, developed in the Naval Postgraduate School's operations research department by Brown, Kline, Rosenthal, and Washburn in 2007, calculates speed combinations to achieve fuel savings for a given single ship. This thesis adds additional capacities based upon common principles.

We provide an omnibus tool, the Optimized Transit Tool and Easy Reference (OTTER), with two complementary components: Dynamic OTTER and Static OTTER. Dynamic OTTER is a versatile, interactive transit-planning tool for any ship class that accommodates drill scheduling, a critical feature. The second tool, Static OTTER, is a generic, optimal solution to individual ship transit-speed combinations, in the form of a printable reference sheet that can be used independently. These products are being implemented by United States Navy surface ships and will yield significant fuel savings, equating to additional time on station.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

BOSC	Battlegroup Optimum Speed Calculator
CBG	carrier battle group
CG	guided missile cruiser
CO	commanding officer
DDG	guided missile destroyer
DFM	diesel fuel, marine
DOD	Department of Defense
FFG	guided missile frigate
FY	fiscal year
GAO	Government Accountability Office
GPH	gallons per hour
GPNM	gallons per nautical mile
HR	hour
kts	knots or nautical miles per hour
LCS	littoral combat ship
LHA	landing-helicopter assault
LHD	landing-helicopter dock
LP	linear program
LPD	landing-platform dock
LSD	dock landing ship
NM	nautical miles
NPS	Naval Postgraduate School
OOD	officer of the deck
OTTER	Optimized Transit Tool and Easy Reference
PIM	plan of intended movement
RASP	replenishment-at-sea planner
SAG	surface-action group
TFP	transit fuel planner
TTSC	time to speed change

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

This thesis describes a fuel-saving tool that may be used in daily shipboard operations, at the fleet level, and in planning offices. The transit fuel planner (TFP) developed in the Naval Postgraduate School's Operations Research department by Brown, Kline, Rosenthal, and Washburn in 2007, calculates speed combinations to achieve fuel savings for a given single ship; this thesis adds additional capacities based upon common principles by expanding the optimization to multiple ships and events. This research develops a decision aide that is easy to use and distribute to military operators and planners.

Our optimization tool is dubbed the Optimized Transit Tool and its Easy Reference (OTTER). OTTER is made up of two components. "Dynamic OTTER" enables planners at the ship and group levels to factor in variables such as drills and evolutions (e.g., flight operations and man-overboard exercises) when calculating optimal speed combinations for travel. For example, suppose the Littoral Combat Ship, USS Freedom (LCS1) is required to transit at 19 knots (kts) average speed for 24 hours. The commanding officer (CO) may operate at any speed, so long as the ship stays inside a moving operating window. To meet training requirements, COs often run drills at slow speed and then catch up with the operating window. If a CO runs a four-hour drill at five kts and then accelerates to meet the expected arrival time, the combined speeds will yield extremely high burn rates. Sacrificing drills in this situation would save significant fuel, but this may not be an option. Dynamic OTTER optimally builds drills and evolutions into a schedule while allowing the user to update shaft-limit changes and fuel-curve data.

Dynamic OTTER can also produce a standalone reference sheet of optimal speed combinations for each class of ship, based on known fuel-consumption rates. This reference sheet, "Static OTTER," could be added to CO standing orders for use by the officer of the deck (OOD).

Our results show significant fuel savings at high speeds for cruisers and destroyers, although savings of less than 1% are seen at normal transit speeds of 14 to 20

kts. In contrast, LCS-class ships see enormous savings under the same average transit speeds, adding significant time on station to the fleet at *no additional cost*. OTTER, using fuel curves for the first LCS class ship, could gain an 18% increase in fuel saved, equating to 10,368 gallons or an additional 57 hours on station at 8 kts. Figure A shows significant improvement in fuel economy both with and without scheduled drills.

Figure A. USS Freedom (LCS1) hours earned on station from 24 hour transit

	Speed profile	**Avg burned (GPH)**	**48 hour transit total (gal)**	**Additional Time on station at 8 kts (hrs)**	**Comments**
W/o Drills	19 kts	2,428	116,544	0	Constant speed
W/o Drills	15 kts / 35 kts	1,996	95,827	113	With OTTER
W/ Drills	5 kts / 22 kts	2,537	121,753	0	Catch up
W/ Drills	5 kts / 15 kts / 35 kts	2,221	106,611	83	With OTTER

USS Freedom (LCS1), with an average speed requirement of 19 kts, can earn 113 hours on station by using speed combinations recommended in OTTER with no drills or 83 hours on station with 4 hours of drills at 5 kts.

ACKNOWLEDGMENTS

I would like first to acknowledge my dear companion in this mission of life, Lani Blackburn, who has been my greatest support for 18 years. Lani, I fall in love with you more each day. I hope our children, Weston, Connor, and Emily, will someday find a best friend as I have in you.

There are a few NPS professors I will always remember. Professor Emily Craparo opened my mind to the complexities of linear and non-linear optimization with a smile. Professor, your promise was fulfilled—I lived through it. I would like also to thank Connor McLemore, who skillfully taught powerful, complex ideas using simple tools. Alan Howard and Dan Nussbaum from the Energy Academic Group provided travel funding to San Diego for me to compete in the Athena Conference (and take a first-place award). Brandon Naylor was a talented man that turned out to be a great friend and associate. I would pick you on my team anytime. Finally, I thank the professors and staff in the Operations Research Department for their professionalism and the knowledge they imparted to me.

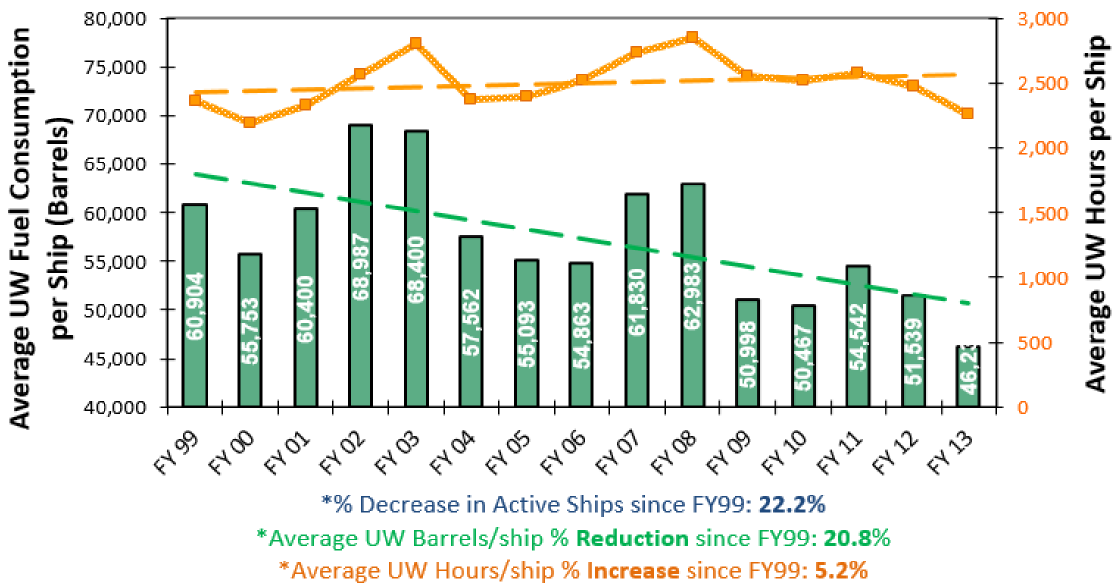
THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. BACKGROUND

Over the past 15 years, U.S. naval ships have consumed an annual average of nearly 500 million gallons of marine diesel fuel (DFM) at an estimated annual cost of $2 billion (Pehlivan 2015). In 2009, the Navy established aggressive goals for reducing consumption of energy at sea (DODLIVE 2015). Since that announcement, ships have consumed approximately 20% less fuel, with fiscal year (FY) 2013 consumption at the lowest, totaling 345 million gallons (Pehlivan 2015). Figure 1 depicts average underway barrels and hours per ship.

Figure 1. Average underway barrels of oil and time (hours) per ship



Total underway fuel consumption rates for FY 1999 through 2013. The overall decrease in fuel consumption per ship reflects conservation measures, despite a concurrent increase in underway hours per ship. Source: Hasan P (2015) Email message to the author, June 19.

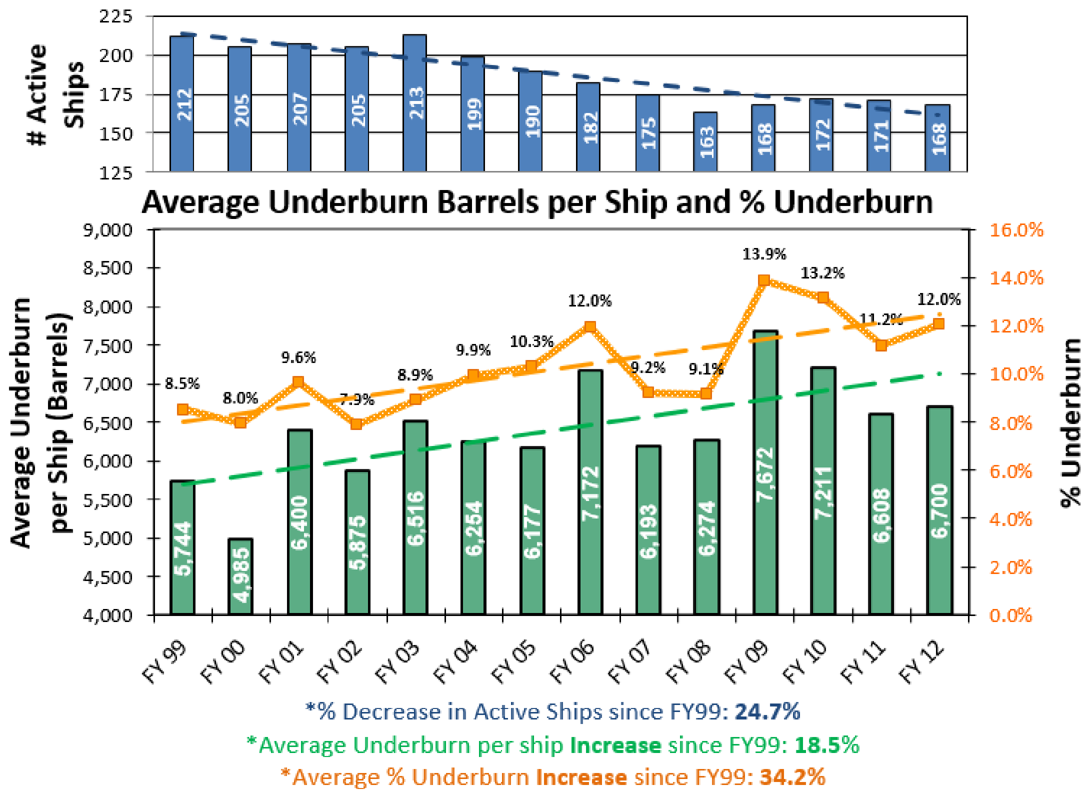
Steam and gas turbine U.S. Navy ships are powered by multiple engines. The term “engineering configuration” refers to a ship-specific available combination of engines. A ship with four General Electric LM2500 gas turbines, for example, may be

operated in three different engineering configurations: one, two, or four engines online, with each additional engine adding to the available horsepower and fuel burn rate of the ship (Schrady et al. 1996). For a ship to reach higher speeds, more horsepower and often more engines are required. Ship speed limits may be imposed upon each engine configuration because of safety concerns determined by engineers (Ibid). Ships record fuel burn rates at each engineering configuration during performance trials; this thesis refers to the resulting fuel burn data as “fuel curves.”

Fuel usage aboard naval ships has steadily decreased since 2009 due to conservation measures. Simultaneously, ships are being removed from the fleet due to budget cuts, thereby increasing average underway time per ship. Figure 2 depicts this trend, as well as an increase in underburn, defined as the fuel saved annually on a specific ship, as compared with a baseline three-year average (FY 1999–2001). Fleet efficiency is imperative if the Navy is to sustain its mission and reduce fuel consumption.

Fuel-saving measures needing structural modifications require a significant investment of money in the beginning of the program, ideally earning back the money invested within a few years of implementation. Software improvements can also provide fuel savings, but they require managers that maintain support for the software development and application. Each of these technologies adds to the efficiency of the fleet. As RADM Thomas Eccles said, “No single technology will enable the Navy to achieve its energy goals” (McCoy 2012).

Figure 2. Average barrels per ship and percent underburn annually

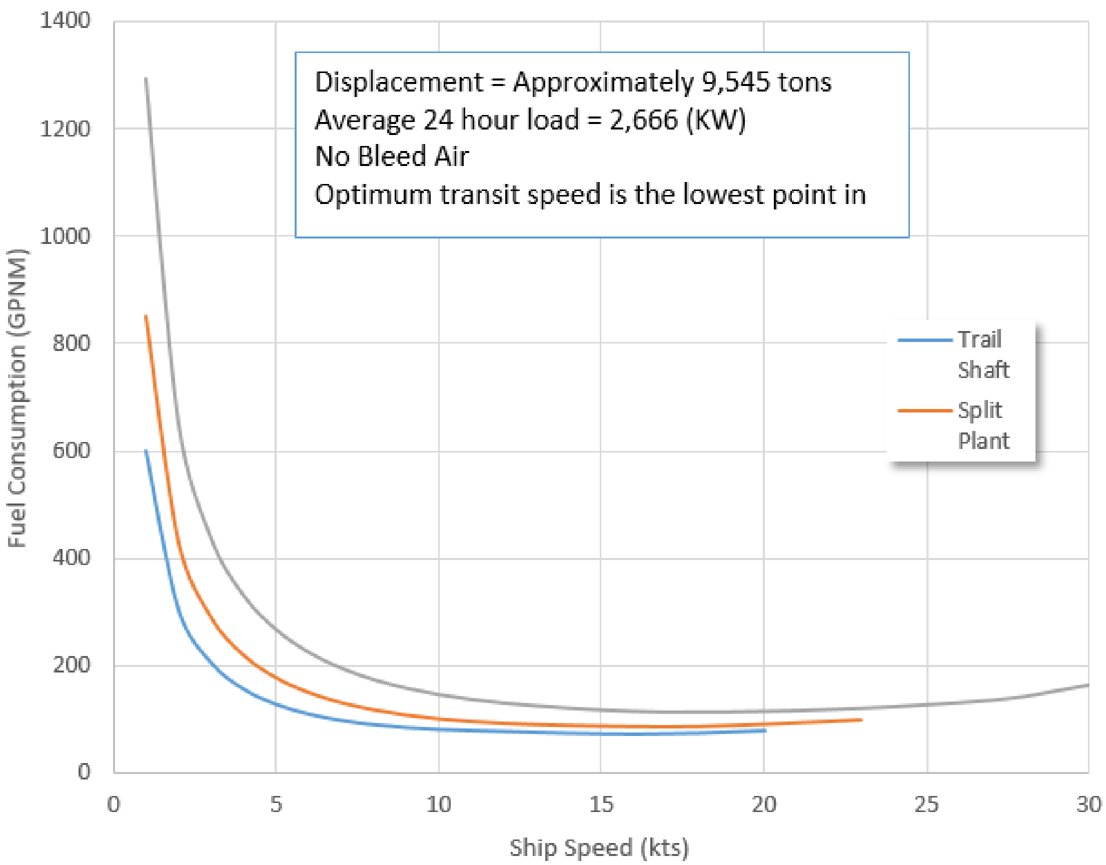


Annual average underburn per ship and percent underburn for FY 1999 through 2012. Underburn is defined as the amount of fuel saved compared to a baseline established from FY 1999—FY 2001, inclusive. Note the overall increase in fuel saved per ship due to conservation. Source: Hasan P (2015) Email message to the author, June 19.

While a number of fuel-saving measures have been implemented in recent years, improvements in operational transit speeds have been limited. Commanding officers do use fuel curves to configure ship's propulsion plants for optimal efficiency at given constant speeds. If time or distance constraints demand a speed that is less than optimal, COs often apply common sense speed alternatives to save fuel; for example, a ship may drive at higher speeds for a time and then switch to a slower, more economical speed while maintaining a satisfactory position from a mission perspective. Figure 3 shows fuel-burn rates in gallons per nautical mile (GPNM) vs. ship speed in knots (kts) for a guided-missile cruiser (CG). Driving at the minimum point of the lowest curve (15.5 kts at trail shaft in Figure 3) at constant speed would return the absolute minimal burn rate

for a given vessel. Fuel curves for each ship analyzed in this thesis are included in Appendix A.

Figure 3. CG47 class total-ship fuel consumption GPNM vs. speed (with stern flap)

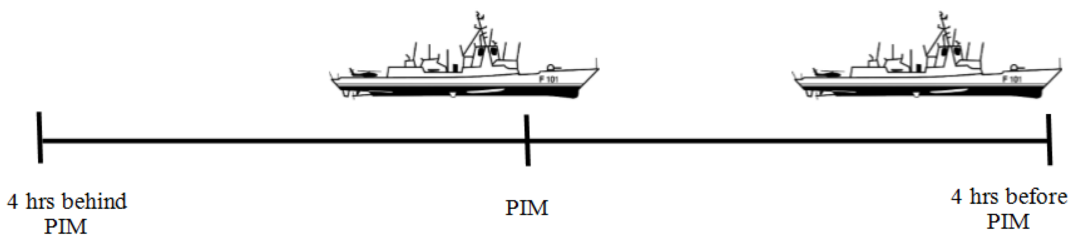


CG fuel burn rate displayed in gallons per nautical mile (GPNM) vs. ship speed (kts). Adapted from Pehlivan H (2015) Email message to the author. June 19.

United States naval ships often operate within established moving boundaries called *plan of intended movement (PIM) boundaries* (NAVDORM 2012). A *PIM window* is an operating window that moves at a constant transit speed; its boundaries are typically four hours to the front and rear of the average speed point (see Figure 4). Traveling at a constant speed at the center of a PIM window is generally impossible due to conflicts with operational tasking and training requirements. To meet these requirements, evolutions are run at lower speed down the intended track, causing the ship to lag within

the PIM window and requiring it to "catch up" with other ships after the drill is complete. Such training requirements complicate the problem of optimizing transit speed to minimize fuel consumption. Often, a ship will travel at a combination of higher and lower speeds to accommodate training requirements. There exist optimal combinations of burn rates for several constant required speeds that are more efficient than the original burn rate, depending on specific ship configurations and respective burn rates.

Figure 4. PIM window example



PIM window is based upon a four-hour allowance forward and behind of the allowed average speed determined by higher authority.

B. LITERATURE REVIEW

The transit fuel planner (TFP) developed in the Department of Operations Research at the Naval Postgraduate School (NPS) prescribes optimal transit speeds to minimize fuel consumption based on the propulsion-plant configuration for a single ship (Brown et al. 2007). This thesis introduces the Optimized Transit Tool and Easy Reference (OTTER), which uses the concepts derived in the TFP to find optimal speeds and implement them in a useful manner (Brown, et al. 2011).

NPS student S. Fonte compares several fuel-saving techniques in his 2009 thesis, as shown in Table 1. The technique with the highest savings per year across his analysis was based upon efficient engineering configuration. Fonte noted that after the introduction of the TFP, follow up work was "waiting to be explored" (Fonte 2009). In 2014, NPS student Dustin K. Crawford proposed follow-up work to modify the TFP,

citing a need to analyze ships traveling together in a carrier battle group (CBG) or surface-action group (SAG).

Table 1. Fuel saving techniques and their estimated savings

At $100/barrel			
Technique	Savings/yr/ship ($K)	Savings/yr/SD Fleet ($K)	10-yr Savings at 0% disc ($K)
Practice Single Generator Ops	881	9,690	96,895
Modify Plant Status During RMD	44	920	9,200
Reduce Use of Prairie/Masker Air	38	789	7,886
Employ Duty Radar w/ 2 Aegis Ships	12	256	2,555
Allow for a Flexible C3F OPAREA	7	139	1,389
Use Auto-Pilot During Long Transit	6	86	860

As clearly seen, operating configuration has the most effect by far on fuel savings. Source: Fonte S (2009).

In 2015, Naval Systems Command (NAVSEA) 05Z created a tool that could be used onboard ships that optimize SAG or CBG transits that are required to maintain a steady state throughout the transit. This tool is called the Battlegroup Optimum Speed Calculator (BOSC). The limiting assumptions to this model are that the ships must maintain a constant speed throughout the transit and stay within a constant distance from each other. BOSC adds up the fuel burn rates for the different ships and returns the best fuel burn rate for the given group. For example, if a CG SAG was required to transit at 19 kts average speed, the calculator would tell you that 16 kts would be more efficient, given more time was available. BOSC, helps planners to schedule transits at a more optimal average speed (Pehlivan 2015). BOSC does not incorporate operational requirements such as drills and evolutions, constraining the ships to maintain a steady state speed throughout the transit. Additionally, it does not take into account the potential savings the TFP offers for ships if the SAG cannot travel at the optimal speed throughout the transit.

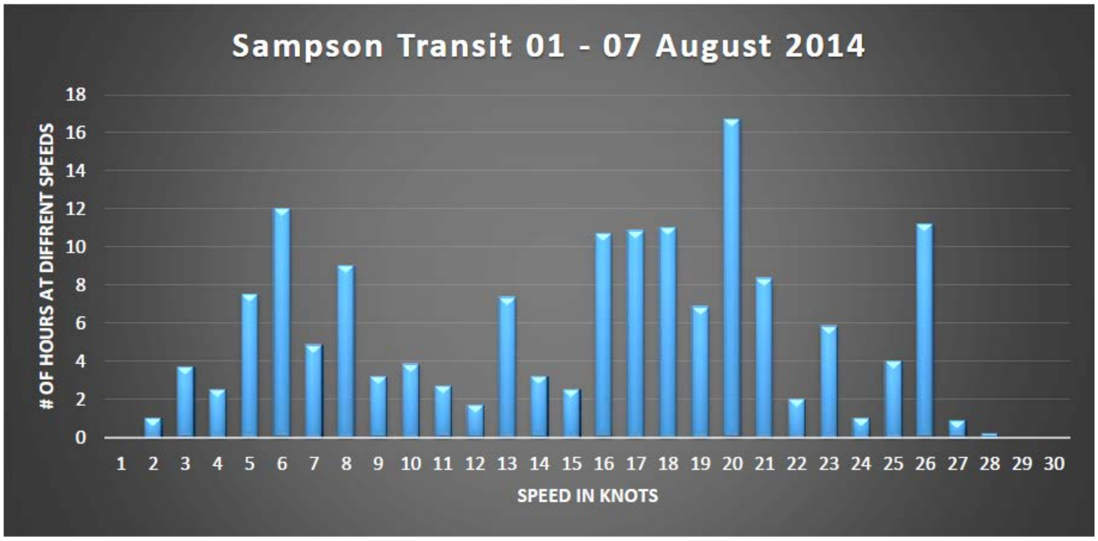
Naval Postgraduate School’s Energy Academic Group in 2015 commissioned a research project to determine the effect of ship configuration on fuel usage for a CBG on station (Naylor 2015). It was noted during the study that ships often operated with all

engines running during certain evolutions in order to be prepared for quicker response. Operating at an optimal engine configuration, CG and DDG class ships would spend between 50 and 100 percent more time conducting operations before needing to refuel. This study recommended coordination between CBG components in order to relax the requirements upon the CG and DDG escort ships in order to increase their operational capability.

The LCS is the newest class ships added to the Navy fleet and has as of today received little analysis with regards to fuel usage. In 2014, the Government Accountability Office (GAO) reported that “Fleet users said LCS fuel constraints contributed to a low average transit speed that, coupled with the very long distances ships have to travel within the 7th Fleet theater, make it hard for LCS to easily or efficiently get around the theater” (Government Accountability Office [GAO] 14-749 2014).

In the summer of 2014, the Navy conducted an experiment directing USS Sampson (DDG 102) to travel to Hawaii and back at a PIM speed of 15.5 kts, the minimum point on Sampson’s fuel curve. This is the ship’s most efficient speed, if maintained constantly. The ship was outfitted with a monitoring system that recorded fuel-burn rate and speed at 10-minute intervals throughout the transit. As shown in Figure 5, several factors contributed to decreased efficiency. Less than three hours was spent at optimal speed. Two-thirds of the time was spent at trail-shaft configuration, while the other third was spent at either full power or split plant (SURFPAC 2015). Maintaining an optimal transit speed of 15.5 kts could have saved 20,334 gallons of fuel, or 12.2%, equating to an additional 30 hours at 8 kts on station. The experiment demonstrated that a ship maintaining a constant speed of 15.5 kts for a seven-day transit is unrealistic, given the training and operational requirements a commander must fulfill. A primary objective of this thesis is to provide a decision tool that promotes awareness of fuel consumption while accounting for the operational realities inherent in naval operations.

Figure 5. USS Sampson transit 2014: Time spent at various speeds during transit



Transit data from USS Sampson summer 2014. USS Sampson (DDG 102) transit from Hawaii to San Diego shows most transit time was spent at various high and low speeds, due to drills and evolutions. Less than three hours was spent at the optimal speed of 15.5 kts. Source: Richards M (2015) Email message to the author, September 11.

Recent fuel-saving measures that have been implemented on board Navy ships include:

- Solid-state light-emitting diodes (LEDs), which save 50% to 80% on energy-related fuel requirements but cost 40 times that of the existing fluorescent bulbs at $158 per bulb. Each bulb has an expected 10 year life span, which is long enough to recoup the setup cost when compared to traditional bulb replacements (U.S. Navy 2014).

- A real-time monitoring program (the Shipboard Energy Dashboard), which shows how power requirements can be reduced while maintaining system performance and reliability requirements. This was developed by NAVSEA and is a decision tool that enables the user to modify operating behavior to save fuel. It is estimated to save less than one percent of fuel on average (DODLIVE 2015).

- Stern flaps installed on new ships and retrofitted on many existing ships modifying the water flow under the ship’s hull reduce drag and turbulence, thereby reducing overall hull resistance. Savings are estimated to be between 2 and 7%, recouping installation costs within the first 2 years of use (Ibid).

- The Smart Voyage Planning Decision Aid is a computer software module that uses a ship's Electronic Chart Display and Information System and information from meteorologists to determine an efficient and optimized route accounting for currents, waves and weather (Ibid). Fleet adoption of this system is in the initial stages.

C. OBJECTIVES

We develop a mathematical model incorporated in an Optimized Transit Tool and its Easy Reference dubbed "OTTER." A major objective of this thesis is to determine the potential fuel savings of multiple ships moving together in convoy, as well as the operational requirements involved in keeping all such ships within a prescribed PIM window.

OTTER is made up of two components. "Dynamic OTTER" enables planners at the ship and group levels to factor in drills and evolutions, which occur typically at slow speeds (5 kts), when calculating optimal speed combinations for travel. For example, the USS Freedom (LCS1) is required to transit at 19 knots (kts) average speed for 24 hours. The commanding officer (CO) may operate at any speed, so long as he or she stays inside a moving operating window. To meet training requirements, COs often run drills at slow speed and then catch up with the operating window. If a CO runs a four-hour drill at five kts and then accelerates to 22 kts meet the expected arrival time, the combined speeds will yield extremely poor burn rates when averaged. Sacrificing drills in this situation would save significant fuel, but this may not be an option. Dynamic OTTER optimally builds drills and evolutions into a schedule while allowing the user to update shaft-limit changes and fuel-curve data.

Dynamic OTTER can also produce a standalone reference sheet of optimal speed combinations for each class of ship, based on known fuel-consumption rates. This reference sheet, "Static OTTER," would be a valuable addition to CO standing orders for use by the officer of the deck (OOD).

In the analysis section of this thesis, we calculate the average and 90th percentile distances between ships traveling inside a common PIM window. Additionally, we calculate and analyze the time required until a CO must change speeds in order to stay

within the PIM window for various situations. These two values give the CO knowledge to support maneuvering decisions in transit routes.

D. SCOPE, LIMITATIONS AND ASSUMPTIONS

This thesis focuses on United States Navy surface-fleet, fossil-fuel ships. This flexible tool can serve as a basis for additional, comprehensive planning tools. While this thesis discusses a particular set of ships, further study of fuel optimization may be applied to *any* engineering platform with multiple fuel/distance curves.

Oceanic winds and currents affect ship speed during transit. To employ the static reference sheet, the OOD must determine the effect of current and wind using existing methodology before applying results from OTTER. If, for example, the required ship speed over ground is 12 kts, but there is a 2-kts current pushing back, the OOD adjusts the speed through water to 14 kts. We assume basic seamanship skills for simple navigation calculations using speed and direction manually entered into the calculation using Dynamic OTTER.

While Dynamic OTTER allows for the scheduling of drills in the short term, Static OTTER requires that the user calculate the new speed of advance after drills are complete. This new average speed can be used with the Static OTTER reference sheet to determine the most efficient speed combinations for the remaining transit.

E. CONTRIBUTIONS AND OUTLINE

The main contributions of this research are the proving and application of simple linear optimization of fuel curves across engineering configurations and the development of OTTER as a tool to implement this research in the fleet. The mathematics behind the linear programming model and how it was implemented are demonstrated in Chapter II. Static and Dynamic OTTER description and implementation tools are described in Chapter III. After providing examples and analysis results in Chapter IV, this thesis concludes with recommendations for implementation and potential future work.

II. MODEL

OTTER solves a linear program (LP) similar to the TFP in order to determine the optimal combination of speeds for each of the ships in a convoy, subject to the constraints that each ship arrive at the desired destination at a prescribed time while performing any required drills. The time and distance values used in the formulation account for requested drills, ocean current, starting and ending distance from the center of PIM, and the overall effect of the scheduled drills upon forward progress in reference to center of PIM. Although the relative positioning of the ships during transit is an important practical consideration, the LP does not explicitly calculate or prescribe individual ships' positions as a function of time. Rather, after performing the optimization, OTTER determines a schedule of speed changes to guarantee that each ship remains within the PIM window.

Dynamic OTTER applies the faster of the two speeds first, putting the ship toward the forward half of the window. This models the current CO behavior and is most realistic. Drills are scheduled according to specified user input times. The schedule is broken down into time increments in number of minutes specified by the user.

The linear optimization model is shown next, followed by an explanation of the variables and constraints. This model simply calculates the most efficient speeds to travel at for a specified time and distance and is modified from the TFP model (Brown et al. 2007). The schedule builder is described in great detail in Chapter III.

A. TRANSIT FUEL PLANNER LINEAR PROGRAM (TFP-LP)

Indices and sets:

$v \in V =$ Vessels {CG, DDG1, DDG2, LCS1, LCS2, LHA1, LHA6, LHD1, LHD8, LPD4, LSD41, FFG7}

$s \in S =$ Speed levels $\{1, 2, 3 \ldots 40\}$

Data [units]

Distance	Required transit distance [nautical miles]
$Speed_{v,s}$	Speed of level *s* for vessel *v* [kts]
$BurnRate_{v,s}$	Fuel burn rate for vessel *v* operating at the most efficient plant configuration at speed level *s* [gallons per hour]
AlTime	Allotted time to complete transit [hours]

Decision variables [units]:

$Time_{v,s}$ Time for vessel *v* to spend at speed level *s* [hours]

Formulation:

$$\underset{Time}{Min} \sum_{v,s} Time_{v,s} * BurnRate_{v,s}$$

s.t.

$$\sum_{s \in S} Speed_{v,s} * Time_{v,s} \geq Distance \qquad \forall v \qquad (1)$$

$$\sum_{s \in S} Time_{v,s} = AlTime \qquad \forall v \qquad (2)$$

$$Time_{v,s} \geq 0 \qquad \forall v, s \qquad (3)$$

B. DISCUSSION

For each ship, the model determines the optimal amount of time the ship should spend in each of a set of speed levels. The objective is to minimize the total fuel consumed by all ships. Constraint set (1) ensures that each vessel covers at least the required distance. Constraint set (2) ensures that the sum of the suggested times are equal to the allotted time constraint. Constraint set (3) ensures that the ship times at each speed

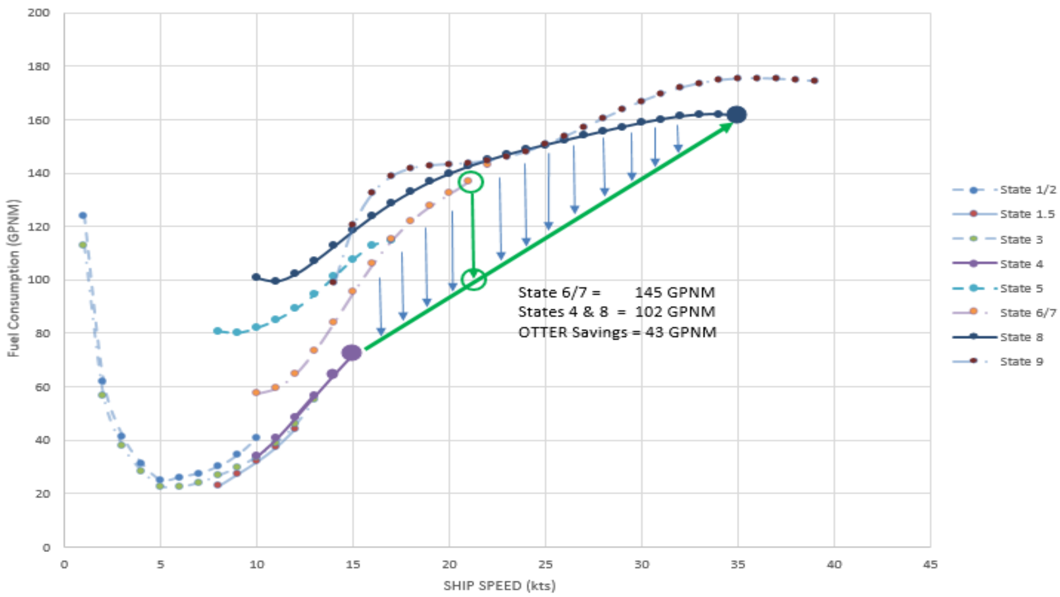
are non-negative. Each ship has unique speed profiles and fuel burn rates. Speeds chosen for a specific transit are only chosen from the specific ship's profile ensuring feasibility.

For a SAG with 10 vessels, the optimization model contains 300 decision variables and 320 constraints. It solves in 0.5 seconds on an Intel 2.4GHz, 32-bit laptop with 4GB RAM.

Figure 6 walks through an example of how this optimization works using the LCS1 class ship. The states listed in the figure are the various engineering modes available to the LCS1. The straight line on connecting state 4 and 8 is the fuel burn rate possible if the ship travels at combinations of 15 kts and 35 kts. We present the following example:

- IF: a speed of 22 kts is ordered to be maintained, on average,
- THEN: 65% of the time should be spent at 15 kts in "state 4" mode
- AND: 35% of the time should be spent at 35 kts in "state 8" mode,
- RESULTING: in a savings of 468 gallons per hour (GPH) or 43 GPNM.

Figure 6. LCS1 class total ship fuel consumption GPNM vs. speed (with stern flap)



An example of an optimized speed combination of 15 kts and 35 kts. LCS1 fuel burn rate displayed in gallons per nautical mile (GPNM) vs. ship speed (kts). The OTTER solution at 22-kts average speed returns 102 GPNM instead of the 145 GPNM in state 8 only. Adapted from Pehlivan H (2015).

It is important to note that in an optimal solution, each ship will spend a nonzero amount of time traveling at most two speeds, excluding drills. This principle can be proven by first assuming the negation. Assume there are three speeds that minimize the average fuel consumption for a given speed. These three speeds on Figure 6 would form a triangle. The minimum burn rate on this triangle would be found along the lowest edge which is a combination of exactly two points. Therefore, proving that as time segments become infinitesimally small, there will always exist at least one but at most two speeds that will be optimal.

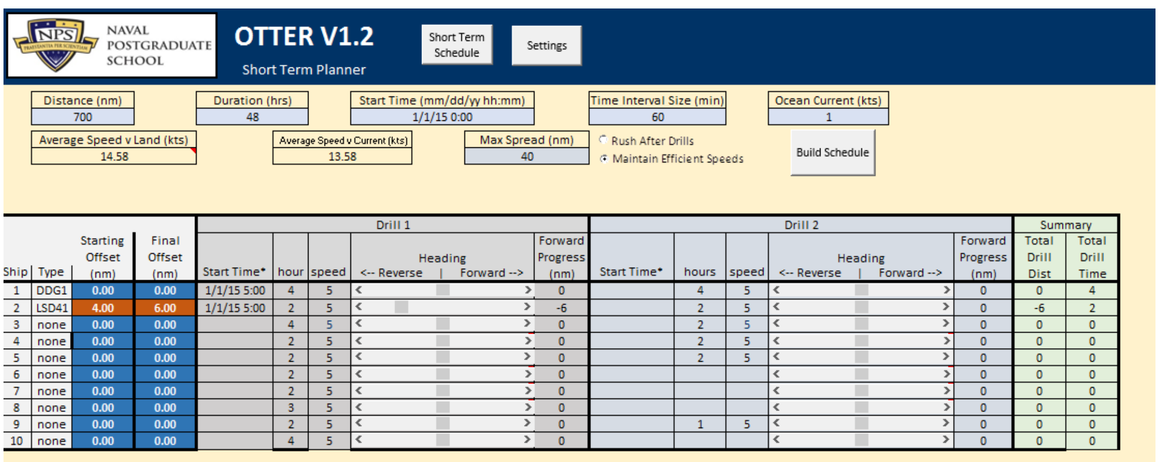
III. THE USER INTERFACE

This chapter describes the user interfaces for Dynamic OTTER and Static OTTER.

A. DYNAMIC OTTER

Dynamic OTTER solves for the optimal speed combinations for the given engineering plant configurations, constrained by user-defined drill periods. The user sets the drill time, duration, and effect on forward progress down track as input, as seen in Figure 7. Dynamic OTTER is built in the Visual Basic for Applications (VBA) language in the Microsoft Excel framework.

Figure 7. Dynamic OTTER input

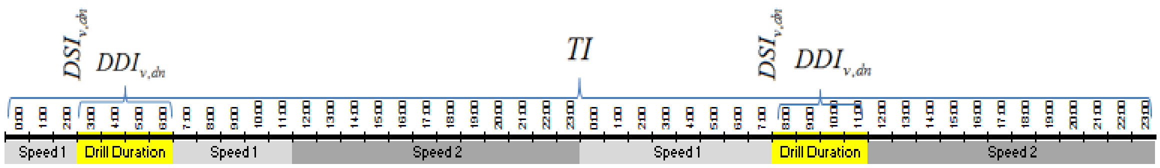


Dynamic OTTER requests transit distance and time, start time, time interval and the effect of ocean current on the transit. The user can add two separate drill starting times, durations, and effects on transit.

Dynamic OTTER's schedule builder output was inspired by the NPS CBG study done by Naylor (Naylor 2015). The study used a tool called the Fuel Usage Study Extended Demonstration (FUSED) which created a ship schedule by hour allowing the scheduler to analyze the fuel usage of the ships over time. OTTER's schedule builder output allowed calculations such as distance traveled, distance between ships in the

group, and cumulative fuel used. It also enables the scheduling of drills and optimization of the remaining time and distance values. A pictorial representation of an output schedule that could be built using Dynamic OTTER can be seen on Figure 8.

Figure 8. Schedule builder timeline



Timeline for a 48-hour transit scheduled into one-hour time increments (*TI*) with two four-hour drills (DN) scheduled. The drill event is annotated by a start time ($DSI_{v,dn}$), drill speed ($DS_{v,dn}$) and a duration ($DDI_{v,dn}$) for each vessel.

1. Dynamic OTTER Schedule Builder Pseudocode

Sets:

- Ships (CG, DDG, etc.) V
- Drill numbers (1, 2) DN
- Time intervals (1, 2, 3...) TI
- Speed options (1, 2) SP

Input:

- Distance to travel (nm) D
- Time for transit to be complete (hrs) T
- Transit start time for ship v (mm/dd/yy hh:mm) TS
- Transit time interval size (min) M
- Ocean current relative to PIM (kts) OC
- Drill start time for ship *v* and drill number *dn* (mm/dd/yy hh:mm) $DS_{v,dn}$
- Drill duration for ship *v* and drill number *dn* (hrs) $DD_{v,dn}$

- Forward progress for ship *v* during drill number *dn* (nm) $DP_{v,dn}$
- Drill speed for ship *v* during drill number *dn* (kts) $DSP_{v,dn}$
- Start offset for ship *v* (nm) SO_v
- Ending offset for ship *v* (nm) EO_v

Compute values:

- Current progress of vessel *v* at time interval *ti* (nm) $CP_{v,ti}$
- Front boundary of PIM window at time interval *ti* FB_{ti}
- Back boundary of PIM window at time interval *ti* BB_{ti}
- Time intervals in transit (integer) $TI = \frac{T*60}{M}$
- Travel time at interval *ti* (mm/dd/yy hh:mm) $TT = \frac{ti*M}{60}$
- Final distance for ship *v* after drills (nm)

$$FD_v = D - \sum_{dn} DP_{v,dn} + EO_v - SO_v \quad \forall v \in V$$

- Remaining time for ship *v* drills (min) $RT_v = TI - \sum_{\mathrm{dn}} DDI_{v,dn} \quad \forall v \in V$
- PIM speed (kts) $PIMSP = \frac{D}{T}$
- PIM window center progress (nm) $PIM = PIMSP*TT$
- Drill number *dn* start intervals for ship *v* (integer)

$$DSI_{v,dn} = \frac{DS_{v,dn} - TS_v}{M} \quad \forall v \in V, dn \in DN$$

- Drill number *dn* duration intervals for ship *v* (integer)

$$DDI_{v,dn} = \frac{DD_{v,dn}*60}{M} \quad \forall v \in V, dn \in DN$$

- Run TFP-LP[1] Optimization uses $FD_v, RT_v \ \forall v \in V$ and returns:
    - 2 optimal speeds (high/low speeds) for vessel *v* (kts)

      $$OSP_{hi,v}, OSP_{lo,v}$$

    - 2 sets (high/low speeds) of remaining time intervals for vessel *v* (integer)

      $$SPI_{hi,v}, SPI_{lo,v}$$

Plan ship schedule:

$CP_{v,ti} = SO_v$

For ti = 1 to *TI*

For each $v \in V$

did_drill = false

For each $dn \in DN$

If $ti \geq DSI_{v,dn} \,\&\, ti < DSI_{v,dn} + DDI_{v,dn}$ then

$SP = DSP_{v,dn}$

$$CP_{v,ti} = CP_{v,ti} + \frac{DP_{v,dn}}{DD_{v,dn}} * \frac{M}{60}$$

did_drill = true

End if

End for

If not did_drill then

If $SPI_{hi,v} > 0 \,\&\, CP_v \leq (PIM + 4 * PIMSP)$ then

$SP = OSP_{hi,v}$

If $CP_{v,ti} \geq (PIM + 4 * PIMSP)$

$FB_{ti} = CP_{v,ti}$ [2]

[1] Optimization method explained in Chapter II

[2] Front and Back boundary calculations described in Chapter II, Section B, Subsection 2

End if

Else

$SP = OSP_{lo,v}$

If $CP_{v,ti} \leq (PIM - 4 * PIMSP\ )$

$BB_{ti} = CP_{v,ti}$**

End if

End if

$$CP_{v,ti} = CP_{v,ti} + SP\ * \frac{M}{60}$$

End if

End for

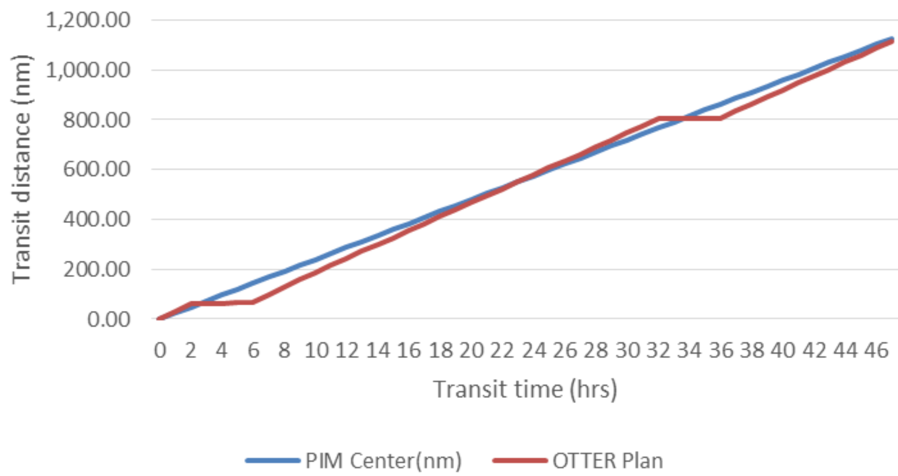
End for

The Dynamic OTTER schedule builder pseudocode builds the arrays and user specified values that will be used to include the ship types used, offset and drill parameters, new and old fuel burned variables. The interval size *M* is chosen from a drop down cell of values that are factors of 60. This ensures that *M* is always an integer. After clearing the old schedule, it updates the schedule headers for each ship chosen on the planner with the appropriate ship types.

The code then loops through the entire range of time intervals scheduled and determines whether to plan a drill, high speed value or low speed value. The modeler sends the ship to the forward half of the operating window by using the faster of the two speeds first. If the chosen time interval is large (60 min), the processing time will be nearly instantaneous.

Now that the schedule builder has calculated the current position $CP_{v,ti}$ for each vessel *v* and time interval *ti*, and we have the PIM window center position *PIM* over each time interval *ti*, we can plot these two for position comparison on the transit. As seen in Figure 9, the OTTER plan maintains a close position to PIM center even with the scheduled drills.

Figure 9. OTTER transit vs. PIM center



Transit distance relative to average speed (PIM center) using Dynamic OTTER schedule builder. This is a DDG Flt 1 48 hour transit at 24 kts average speed with 2 four hour drills scheduled during the transit. Fuel saved during this transit was 70,646 gal or 96 hours of additional time on station compared to typical ship behavior.

After the schedule has been built, the comparative burn rates are calculated based upon a surge speed that is defined by user settings. This surge speed is sub optimum and representative of actual CO behavior during sprint and drift operations. These old burn rates are compiled and compared to the new total fuel burned and values are output as fuel saved. This is also converted to extra time on station by using the ship’s average burn rate at 8 kts. Actual VBA code for Dynamic OTTER can be found in Appendix D.

The OTTER schedule builder runs extremely quickly. It requires approximately 1.0 second to plan a 48-hour transit in 5-minute increments for a SAG with 10 ships. The resulting file size is 671 KB, making it easy to share via email or download.

2. Time Until Speed Change

Another valuable capability this thesis describes is a method of calculating PIM boundaries. The time until speed change (TTSC) is defined as the time (in hours) until a ship is required to change speed to stay within the PIM window. Normally the ship CO must determine when to change speeds in order to stay within the PIM window boundaries. Assuming the ship starts a transit at the center of an authorized PIM window,

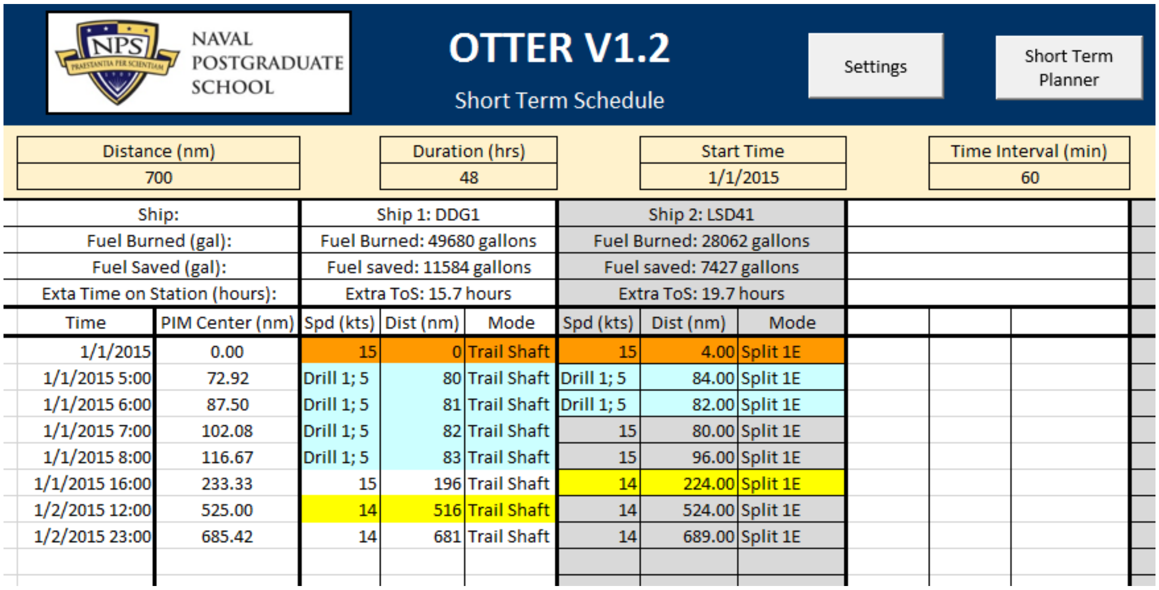
the time to change speed can be calculated for both the front and back of the PIM window.

In the pseudocode, the front boundary FB_{ti} and the back boundary BB_{ti} were saved, recording the time at which a forward or back boundary was reached. These moving boundaries in time are not to be crossed, so they serve as a guide in Static OTTER as well as in our analysis Chapter as TTSC.

3. Dynamic OTTER Output

Dynamic OTTER returns a schedule indicating the PIM center, each ship position, engineering configuration, and speed in each time step. The fuel burned, saved, and equivalent time on station is shown for each ship. The "largest spread" value reported in the header is the greatest difference between ship positions at any point in time. Each ship will stay within the PIM window during the transit. Figure 10 shows the output from Dynamic OTTER, a schedule broken down into time increments for each ship modeled.

Figure 10. Dynamic OTTER output



NAVAL POSTGRADUATE SCHOOL

OTTER V1.2

Short Term Schedule

Settings | Short Term Planner

Distance (nm)	Duration (hrs)	Start Time	Time Interval (min)
700	48	1/1/2015	60

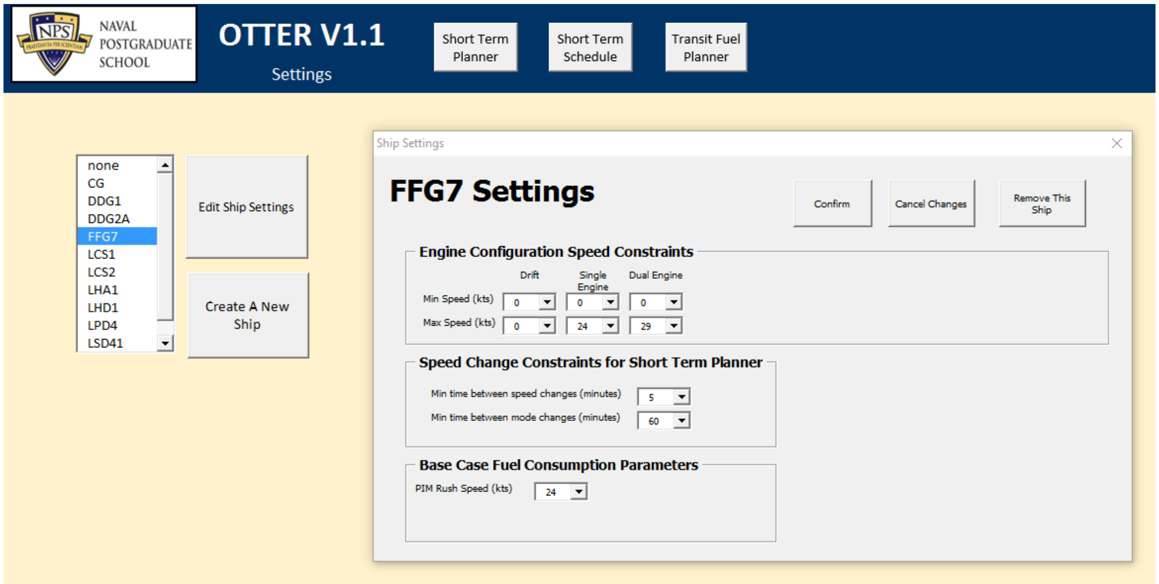
Ship:		Ship 1: DDG1			Ship 2: LSD41		
Fuel Burned (gal):		Fuel Burned: 49680 gallons			Fuel Burned: 28062 gallons		
Fuel Saved (gal):		Fuel saved: 11584 gallons			Fuel saved: 7427 gallons		
Exta Time on Station (hours):		Extra ToS: 15.7 hours			Extra ToS: 19.7 hours		
Time	PIM Center (nm)	Spd (kts)	Dist (nm)	Mode	Spd (kts)	Dist (nm)	Mode
1/1/2015	0.00	15	0	Trail Shaft	15	4.00	Split 1E
1/1/2015 5:00	72.92	Drill 1; 5	80	Trail Shaft	Drill 1; 5	84.00	Split 1E
1/1/2015 6:00	87.50	Drill 1; 5	81	Trail Shaft	Drill 1; 5	82.00	Split 1E
1/1/2015 7:00	102.08	Drill 1; 5	82	Trail Shaft	15	80.00	Split 1E
1/1/2015 8:00	116.67	Drill 1; 5	83	Trail Shaft	15	96.00	Split 1E
1/1/2015 16:00	233.33	15	196	Trail Shaft	14	224.00	Split 1E
1/2/2015 12:00	525.00	14	516	Trail Shaft	14	524.00	Split 1E
1/2/2015 23:00	685.42	14	681	Trail Shaft	14	689.00	Split 1E

OTTER output returns a schedule broken down by time intervals and start-time specified for each ship, showing the optimal speed and engineering mode to be used.

4. Dynamic OTTER Settings

To update ship parameters such as shaft limits or maximum speed, the user completes an interactive form for each engineering configuration, as depicted in Figure 11. This is required when engineering limits are imposed due to engineering casualties, or as higher authority directs. The fuel curves can also be updated after ship performance trials. New fuel-curve data may result in significant changes in the findings for optimal speed.

Figure 11. User-defined settings



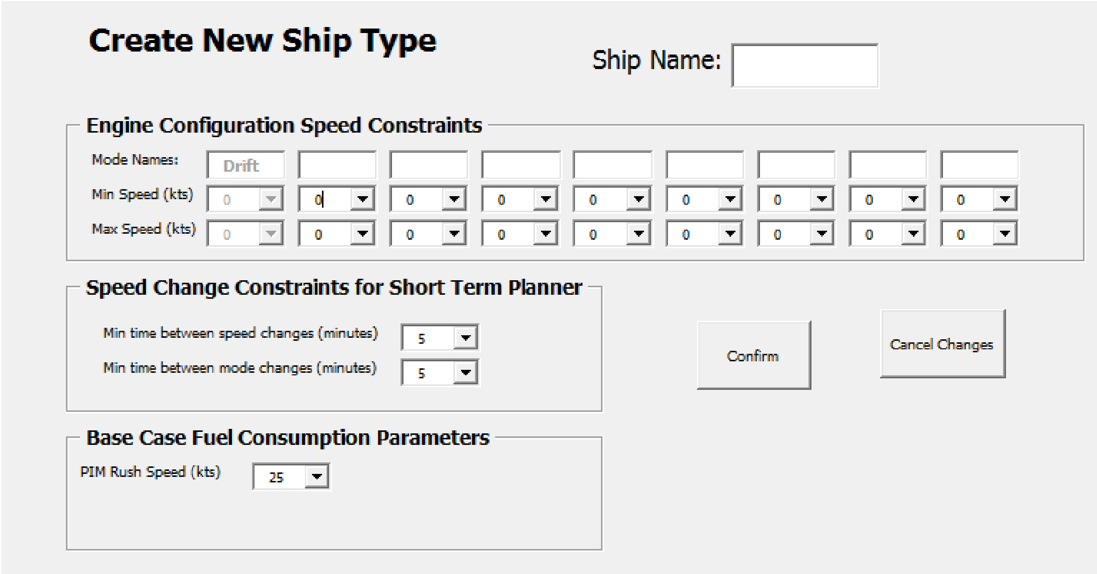
User-defined settings enable the user to update shaft limits for each engineering configuration used. It also enables constraints for time intervals between speed and mode changes.

Users also have the ability to add new ship types (Figure 12) through the settings tab. Users must have ship configuration data such as burn rates and propulsion limits for each mode. When the user inputs this data, the spreadsheet parameters are updated allowing for validation and implementation into both Dynamic and Static OTTER calculations.

When ship types are no longer needed, users can delete the ship from the database through the user-defined settings for that particular ship. This permanent removal deletes the worksheet and all associations to that worksheet in the name manager.

The CO may decide that changing engineering modes impacts the personnel on the ship and therefore wants to limit the frequency. The settings page has parameters such as the minimum time between mode or speed changes to allow for these customizations.

Figure 12. Create a new ship type



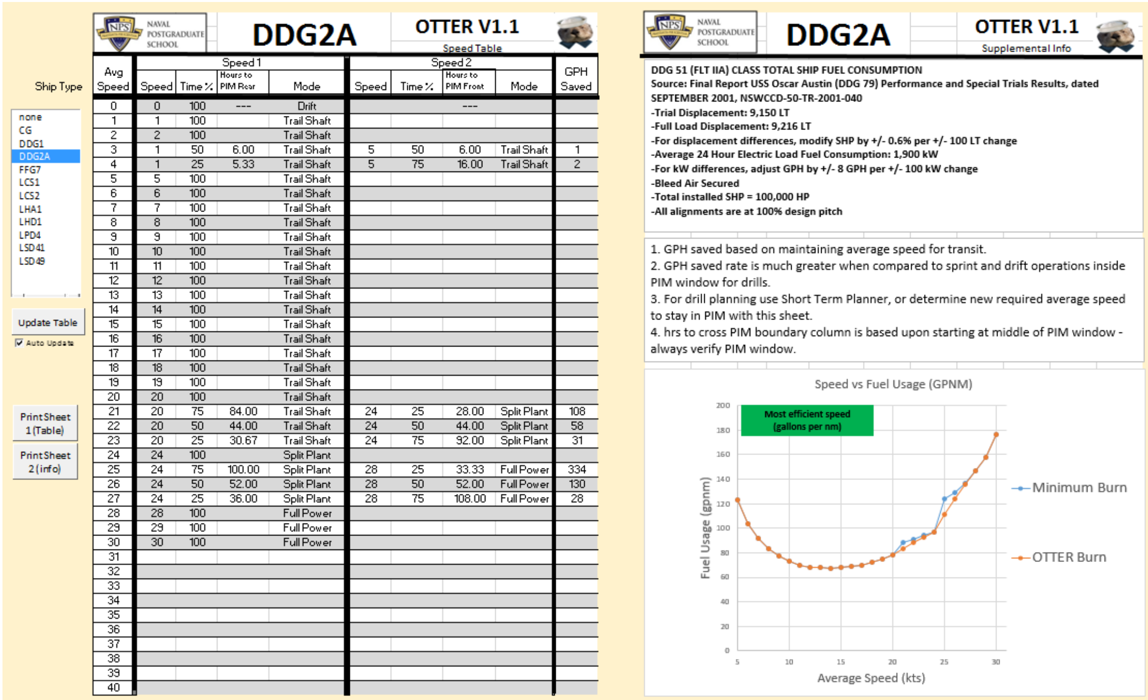
New ship type input form from Dynamic OTTER settings page. User may input propulsion limits which will be saved on a new worksheet in OTTER for new optimal transits and Static worksheet creation.

B. STATIC OTTER

The interface of Static OTTER, depicted in Figure 13, is a user-friendly reference sheet customized to specific ship parameters. Once the proper fuel curves and shaft limits have been verified for a ship, this reference sheet is available for printing. Static OTTER has a speed combination for several requested average speeds. It also gives the percentage of time a user should spend at each of the two speeds. It shows the time until a PIM boundary is met based upon a 4 hour PIM operating window and the ship starting point is from the middle of PIM. Because of these assumptions, operators should always note their position inside the PIM window and ensure boundaries are not violated.

The reference sheet contains detailed instructions and examples. More static tools can be found in Appendix B. Additional sheets can be made and printed from Dynamic OTTER. The spreadsheet also notes the source of the fuel-curve data; this note can be updated by the user through Dynamic OTTER when changes are made to the baseline fuel burn rates.

Figure 13. Static OTTER



Static OTTER can be used to minimize fuel consumption by combining two ship speeds instead of maintaining a single constant speed.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. RESULTS

We now demonstrate the benefits of applying linear optimization to fuel curves in the following example. Suppose LCS1 is in a 48-hour transit and is required to maintain an average speed of 19 kts. Using a standard approach, if the CO decided to run a four-hour drill at five kts and then adjusted the ship's speed to catch up to the expected arrival time (5 kts/21 kts), less-efficient burn rates would be achieved. However, if after running drills the more efficient speed combinations were used (5 kts/15 kts/35 kts), significant fuel would be saved (see Table 2). A CO need not sacrifice drills to save fuel and extend on-station endurance. Dynamic OTTER optimally builds the drill into the schedule at the time specified by the user.

Table 2. USS Freedom (LCS1) with average speed requirement of 19 kts

	Speed profile	Avg burned (GPH)	48 hour transit total (gal)	Additional Time on station at 8 kts (hrs)	Comments
W/o Drills	19 kts	2,428	116,544	0	Constant speed
W/o Drills	15 kts / 35 kts	1,996	95,827	113	With OTTER
W/ Drills	5 kts / 22 kts	2,537	121,753	0	Catch up
W/ Drills	5 kts / 15 kts / 35 kts	2,221	106,611	83	With OTTER

USS Freedom reduction in fuel burn rates when OTTER is used, earning many more hours on station before refueling is required.

A. DATA COLLECTION

For our computational experiments, we used ship performance data collected by Naval Surface Warfare Center, Carderock Division, in West Bethesda, Maryland, during initial sea trials of the lead ship in a class (Pehlivan 2015). Users can update fuel usage data in OTTER as needed accounting for the slight changes in fuel burn as equipment ages.

In order to apply realistic ship transits to the model, we used data collected by Commander Naval Surface Force, U.S. Pacific Fleet Energy Office in 2014 from the USS

Sampson during transit from San Diego to Hawaii and back (Richards 2015). Speed and configuration profile data were collected every 10 minutes for the duration of the transit. This data shows the real transit habits of COs at sea. While a constant transit speed is most convenient to model, it is often unrealistic. Fuel savings were substantially greater using OTTER than using a conservative constant-speed model.

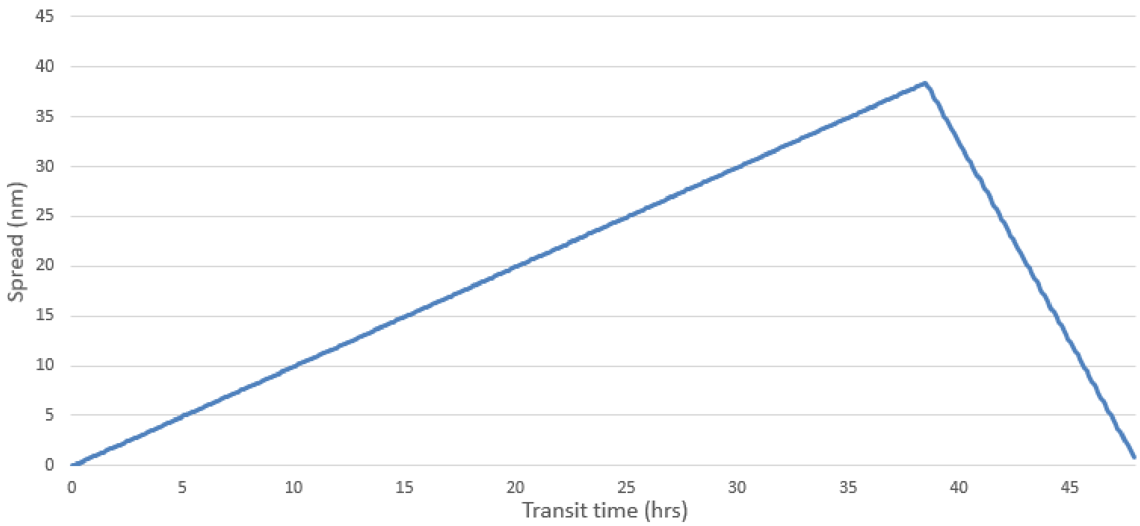
Because burn rates are not stochastic, simulations or trial runs were not required to validate the model. We ran the optimization model over the entire speed range for each ship to produce Static OTTER reference sheets. These new burn rates are independent of other ship transits. Groups of ships could still use reference sheets independently if their constraints are only to remain inside the PIM window. Closer grouping requirements will be addressed in the next section.

B. MAXIMUM SPREAD BETWEEN SHIPS

When a group of ships travels in a SAG, higher authority will dictate the maximum distance between ships during the transit for force protection or logistical reasons. Transiting as a group requires daily planning coordination between COs to ensure these boundaries are not violated. OTTER considers the four hour ahead and behind of the PIM window center as acceptable boundaries for planning. Figure 14 depicts the spread in distance during an example 48-hour transit that a CG and DDG1 would experience following the Dynamic OTTER “Short Term Schedule” recommendations.

With a simple evaluation by the CO or OOD, the spreads could be reduced significantly with no impact on fuel savings. The deviation from the proposed transit plan might be to alternate speeds more frequently than otherwise proposed. Dynamic OTTER has the ability to constrain the spread distance to a specified parameter. This feature does not affect the fuel savings; rather, the effect is seen through more frequent speed or mode changes.

Figure 14. Spread among ships during a group transit of CG and DDG1



Distance between a CG and DDG1 with an average transit speed of 14 kts. These spread distances are due to the differences in proposed transit speeds. The CG travels at 15 kts and then 10 kts while the DDG1 travels at constant 14 kts. The maximum spread between the ships is 37 nm with no additional constraints applied.

Changing some engine configurations may require significant effort for some ships. Intuitively, the larger the spread allowed, the less frequently the ship will have to change engineering modes. If the optimal speeds are followed in their respective ratios as provided by Static OTTER, the fuel savings will be the same, regardless of the frequency of mode changes. In short, the cost of earning a small spread between ships is more frequent engine configuration changes.

Following the recommended OTTER solution with no spread minimization, Table 3 shows the average spread between two ships traveling in a SAG. For example, if a CG and a DDG1 transit in a SAG together, they will, on average be 11 NM apart. Table 4 shows the 90th percentile of the data. Similarly, a CG and DDG1 traveling together would be less than 30 NM apart 90% of the time.

Table 3. Average spread among ships using Dynamic OTTER

	Average Spread (NM)									
	CG	**DDG1**	**DDG2A**	**LCS1**	**LCS2**	**LHA1**	**LHD1**	**ISD41**	**LPD4**	**FFG7**
CG	NA	11	6	30	8	7	14	11	12	10
DDG1		NA	7	34	10	4	12	7	10	5
DDG2A			NA	29	7	3	12	7	11	6
LCS1				NA	29	22	19	24	10	30
LCS2					NA	9	12	10	11	10
LHA1						NA	14	4	11	4
LHD1							NA	13	5	13
LSD41								NA	10	1
LPD4									NA	10
FFG7										NA

With a four-hour PIM window established, the average distance between two ships is shown. This average was calculated over the speed range (1-30 kts for CG) of the slower of the two ships analyzed.

Table 4. 90% of time spread—using Dynamic OTTER

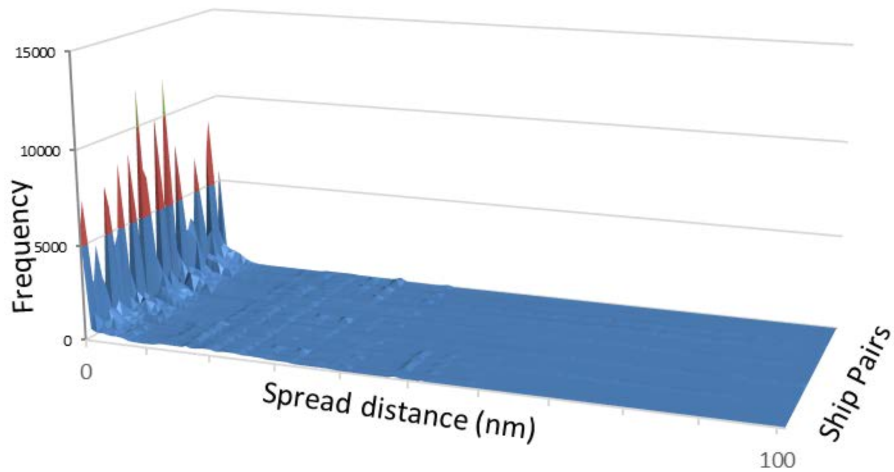
	90% of time spread is less than X (NM)									
	CG	**DDG1**	**DDG2A**	**LCS1**	**LCS2**	**LHA1**	**LHD1**	**ISD41**	**LPD4**	**FFG7**
CG	NA	30	23	77	25	26	35	28	32	26
DDG1		NA	24	89	19	30	33	23	28	20
DDG2A			NA	23	79	30	8	23	30	22
LCS1				NA	77	76	58	76	32	77
LCS2					NA	29	33	30	30	32
LHA1						NA	34	19	30	19
LHD1							NA	33	20	33
LSD41								NA	26	5
LPD4									NA	27
FFG7										NA

With a four-hour PIM window established, 90% of the time the distance between ships will be less than the expressed value.

From each of the combinations in Tables 3 and 4, we created a histogram to represent the number of times during a 48 hour transit (broken down into five minute intervals), that one of the (nCr10,2=45) 45 ship pairs shown on the y axis, across all common speed ranges, would be a particular distance apart. This is a good way of quickly visually portraying the ship pair separation distances. Figure 15 compiles these

48 histograms together into a three dimensional graph. By design the ships are constrained to the common PIM window. This design keeps their spread distances to a minimum, and as one can see from the figure, the majority of the time is spent with very minor distances between them.

Figure 15. Spread values for all ship pairs analyzed

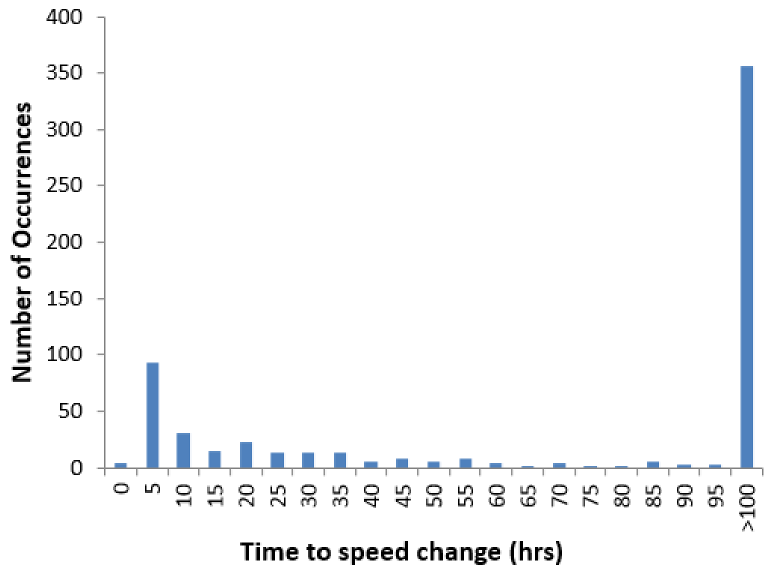


Spread distances (x axis) between ship pairs (y axis) and the frequency (z axis) that particular spread distance occurs.

C. TIME TO SPEED CHANGE

As described in Chapter III, the TTSC values are a measure of the frequency of mode shifts. A low TTSC value means that these shifts occur at higher frequency, likely adding some burden on the engineering crew. TTSC results could be considered highly reasonable with no times less than one hour, and only 3% of situations require a time of one hour. A cumulative summary of TTSC is shown in Figure 16. The TTSC are usually greater than 100 hours which is typically negligible. Individual ship TTSC for the ships analyzed are included in Appendix C.

Figure 16. Frequency of TTSC across all ships modeled



These are TTSC (x axis) vs. number of occurrences (y axis) accumulated over CG, DDG1, DDG2A, LCS1, LCS2, LHA1, LHD1, LSD41, LPD4, LSD49 and FFG7 ships.

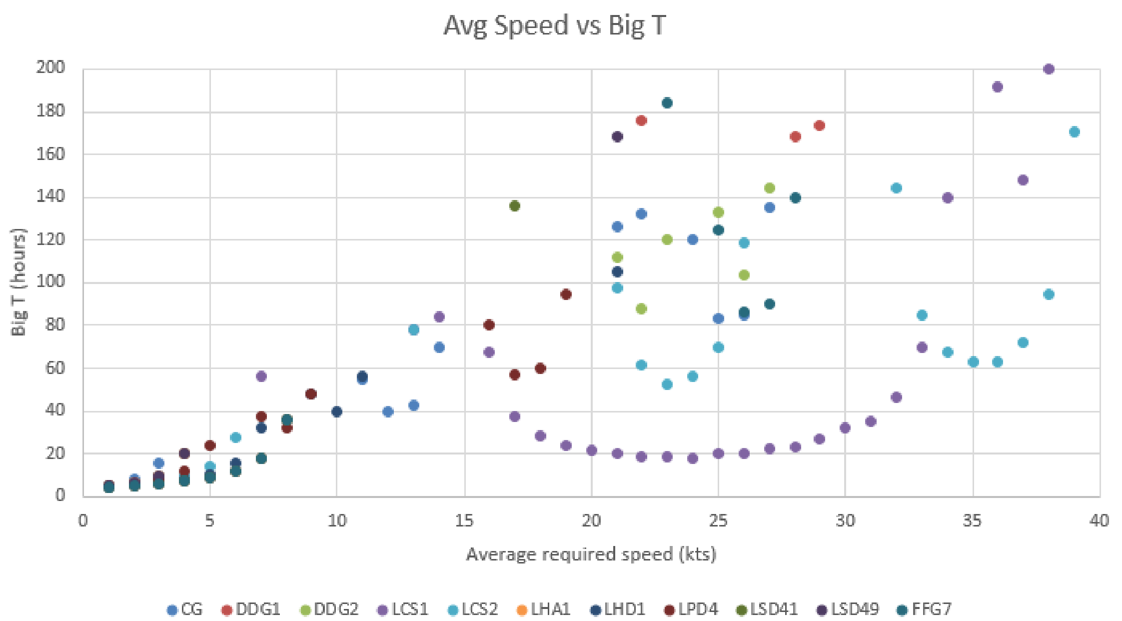
Another metric to represent the additional engineering burden required to stay within a PIM window is a quantity we denote as *big T*. Big T represents the PIM window size in nm divided by the percentage of time spent at one of two optimal speeds. To calculate these values we assume that the ships are operating in a standard four hour window with no drills and there is time to complete the transit. The same variables and definitions from Chapter III are used, with the addition of $PT_{lo,v}$ which is defined as the optimal percentage of time for vessel *v* to spend at *lo* speed or its counterpart *hi* speed. These values are output from the TFP optimizer. *Big T* can be defined as the following:

$$Big\ T = \frac{PIMSP * 4hrs}{(OSP_{hi,v} - PIMSP) * PT_{hi,v}} = \frac{PIMSP * 4hrs}{(PIMSP - OSP_{hi,v}) * PT_{lo,v}}$$

Figure 17 is a graph of every big T value for the range of average speeds for different ship types. It is observable that on average, at lower speeds big T values are lower, meaning that the impactful mode changes would be experienced at average speeds under 10 kts. The outlier to this trend is the LCS1 (shown in purple), where lower big T values

exist at higher transit speeds, owing to the unique engineering plant on that ship that allows greater savings at higher average speeds.

Figure 17. Big T (average speed vs. big T)



Big T times are expressed as the time until a ship is forced to change speeds in order to stay inside of the standard operating envelope using OTTER. This figure shows a standard 4 hour PIM operating window. For example: At 25 kts average speed, LCS1 will have to change speeds at intervals of (20 hours *50%) = 10 hours. In order to stay inside the PIM operating window. Twenty hours came from the y-axis and the fraction is an output of the TFP optimization.

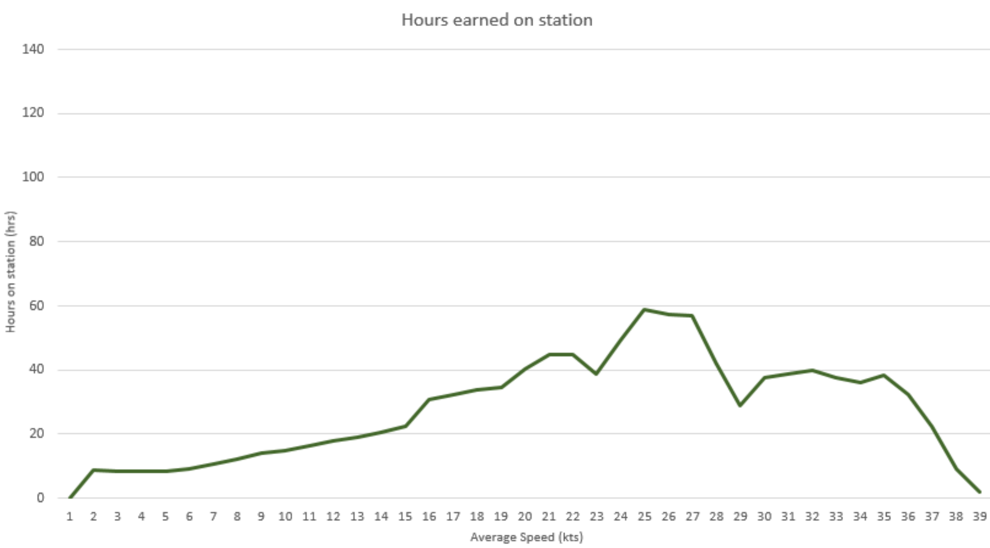
D. ANALYZING MULTI-SPEED FUEL OPTIMIZATION

In practice, COs currently tend to operate in the forward region of their moving PIM window. This allows the CO more flexibility to perform drills and evolutions such as flight operations as needed. Keeping this in mind, Dynamic OTTER models the base-case ship fuel usage as a forward operating ship. It surges the ship to the forward edge of the window using a user-defined surge speed established on the settings page (27 kts for a CG) and then operates at the forward edge until a drill is run or the destination is reached on time.

OTTER then creates a schedule using the optimal speed combinations to position the ship in the forward part of the window, as the CO would desire. The key difference between the base case and the OTTER solution is the use of the inefficient surge speed in the base case. Surging forward is done so frequently for operational reasons that it has been adopted as a common practice called "sprint and drift" (Friedman 2014). The concept is sound, but without knowing the optimal speeds to sprint and drift, the sprint and drift solution is sub-optimal and therefore, unnecessarily wasteful.

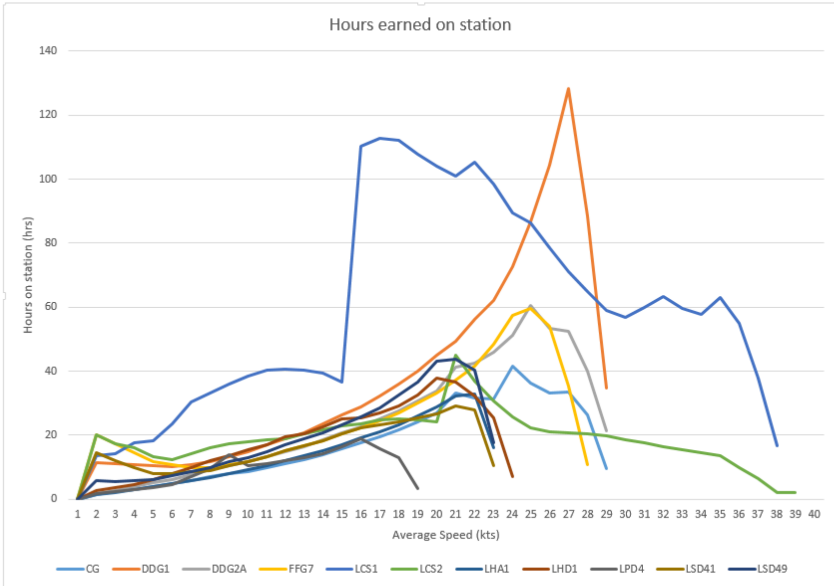
We compared the base case with the Dynamic OTTER solution over 48 hour transits in Figure 18. We assumed no drills were scheduled with a 5 minute incremental resolution. The spread constraint was set at 40 nm and the on station speed was assumed to be 8 kts. For average transit speeds of 15–20 kts, on average a ship could earn 20–35 hours on station. The base case modeled typical CO transit behavior. A more comprehensive graph for each ship is included in Figure 19.

Figure 18. Average hours earned at various average speeds



Additional average hours earned by following OTTER recommendations for a sample of ships traveling in a SAG for a range of average speeds. For example, with a PIM of 15 kts, the ships capable of traveling 15 kts earn about 20 hours of on station time at 8 kts per 48-hour transit, on average.

Figure 19. Detailed hours earned at various average speeds



Additional hours on station (at 8 kts) by following OTTER recommendations for a sample of ships traveling in a SAG for a range of average speeds over a 48 hour transit.

E. CONFIGURATION MATTERS

Ships do not always operate under the most efficient configurations. This may be due to readiness conditions required for an exercise or possibly engineering restrictions. Operating under the optimal engineering-plant configuration and speed are vital components in an efficient transit. For the LCS1 example in Table 2, OTTER proposes a combination of 15 kts and 35 kts at the optimal configuration without drills, resulting in an additional 113 hours on station (at 8 kts) compared to a constant speed. If the user decides to operate under a less efficient engineering mode at the same durations (state 9 vs. state 6/7), the fuel saved will be reduced significantly—from an earned 113 hours on station to 87 hours.

Not all engineering plants are created equal. Boiler plants with only two modes of operation-single or dual boiler mode-do not experience an improvement at all in the majority of their speed ranges (see Appendix B). In contrast, LCS1, has a total of nine engineering configuration modes of operation, allowing for optimization between each

mode giving the LCS class ships enormous opportunity gains in fuel efficiency because of the plant configuration modes.

Applying OTTER to the transit shown in Figure 5 would save 3,329 gallons, which equates to an additional five hours on station at 8 kts-a 1.5% improvement in efficiency. The improvement on the CG and DDG are significant, but not extraordinary. The LCS1-class ship however, could have earned 14% improvement, equating to 37,703 gallons, or an additional 206 hours on station at 8 kts.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis provides a tool that optimizes fuel usage across a group of ships in an impactful way. Benefits of its use are displayed in units of earned time on station to show the operational impact of fuel savings.

B. IMPLEMENTATION CHALLENGES

Designing an intuitive and easily distributable tool for routine use by fleet and shipboard commanders was the goal of this research. Walt DeGrange, a developer of the Replenishment-at-Sea Planner (RASP), laments the indifference that operations-research analyst's typical experience:

> [We] spend months developing the perfect optimal scheduling model by defining the problem, collecting the data, refining the model, enhancing the user interface and including customer feedback and then finally deploying the model. After all this work the customer does not use the model and reverts to legacy practices. What went wrong? (DeGrange 2012)

This thesis faced these challenges of implementation through direct fleet involvement. Briefs were given to the Fleet Forces Command, Commander, Surface Forces, Commander Destroyer Squadron 31 (to include an operational trial in April 2016), Rand Corporation, Office of Naval Research and the Office of the Chief of Naval Operations—Joint Logistics Engagement. OTTER has been tested and distributed with a reference point of contact at Naval Postgraduate School for technical support in the Energy Academic Group.

Implementation of this tool could have taken many different forms, but because we wanted a model that would be directly applicable and used in the fleet, we chose to use Microsoft Excel with no add-ins or external required software. This stand-alone file can be used on Navy computers afloat and ashore. This feature is potentially the most valuable of all.

C. FUTURE WORK

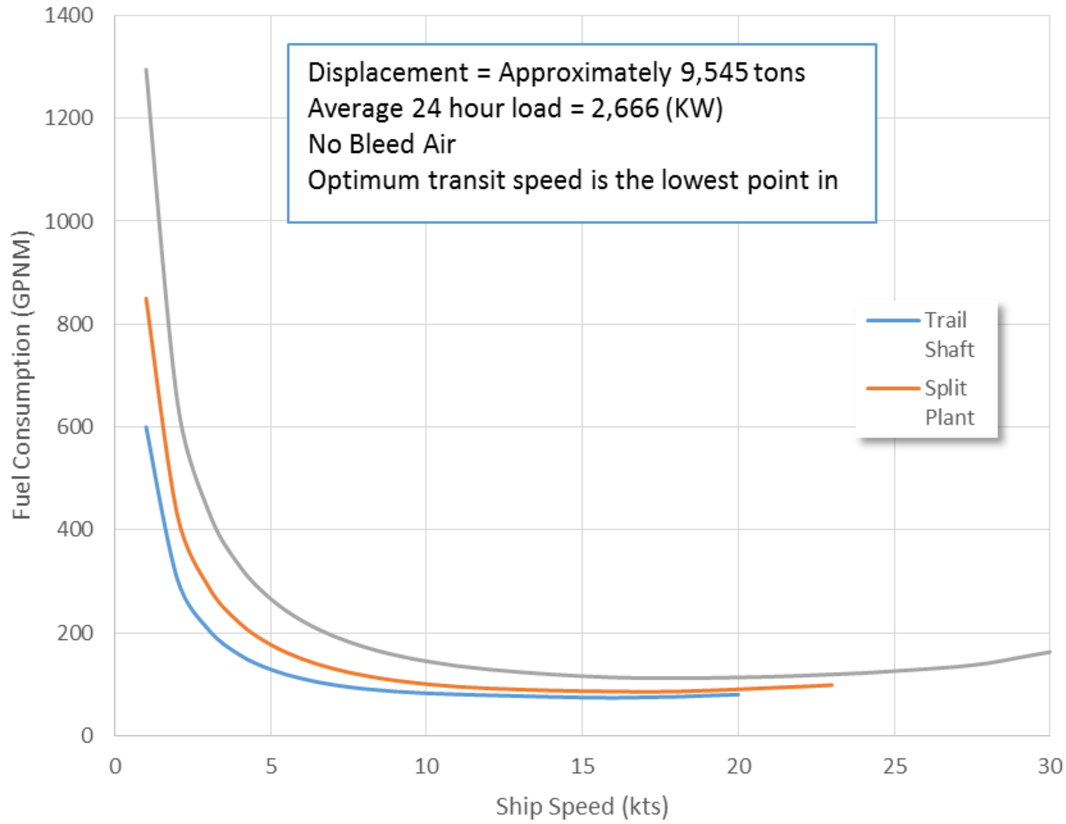
A few modeling variants could yield additional insight. This thesis models speed changes as instantaneous time points. Further modeling of speed ups and slowdowns during these speed changes may result in meaningful results. Another variant of the schedule might build it using closed form calculations for times to speed change, thus eliminating the need to iterate over discrete time periods. Alternatively, a more comprehensive optimization model could simultaneously determine optimal speeds and build a schedule for the battle group.

Application toward other engineering platforms such as train transport or aviation could be explored. Any multi-modal engineering platform with different burn rates could benefit from linear optimization. Implementation of OTTER toward Navy oilers and supply support ships may provide additional fuel savings that are worth investigation.

APPENDIX A. FUEL CURVES

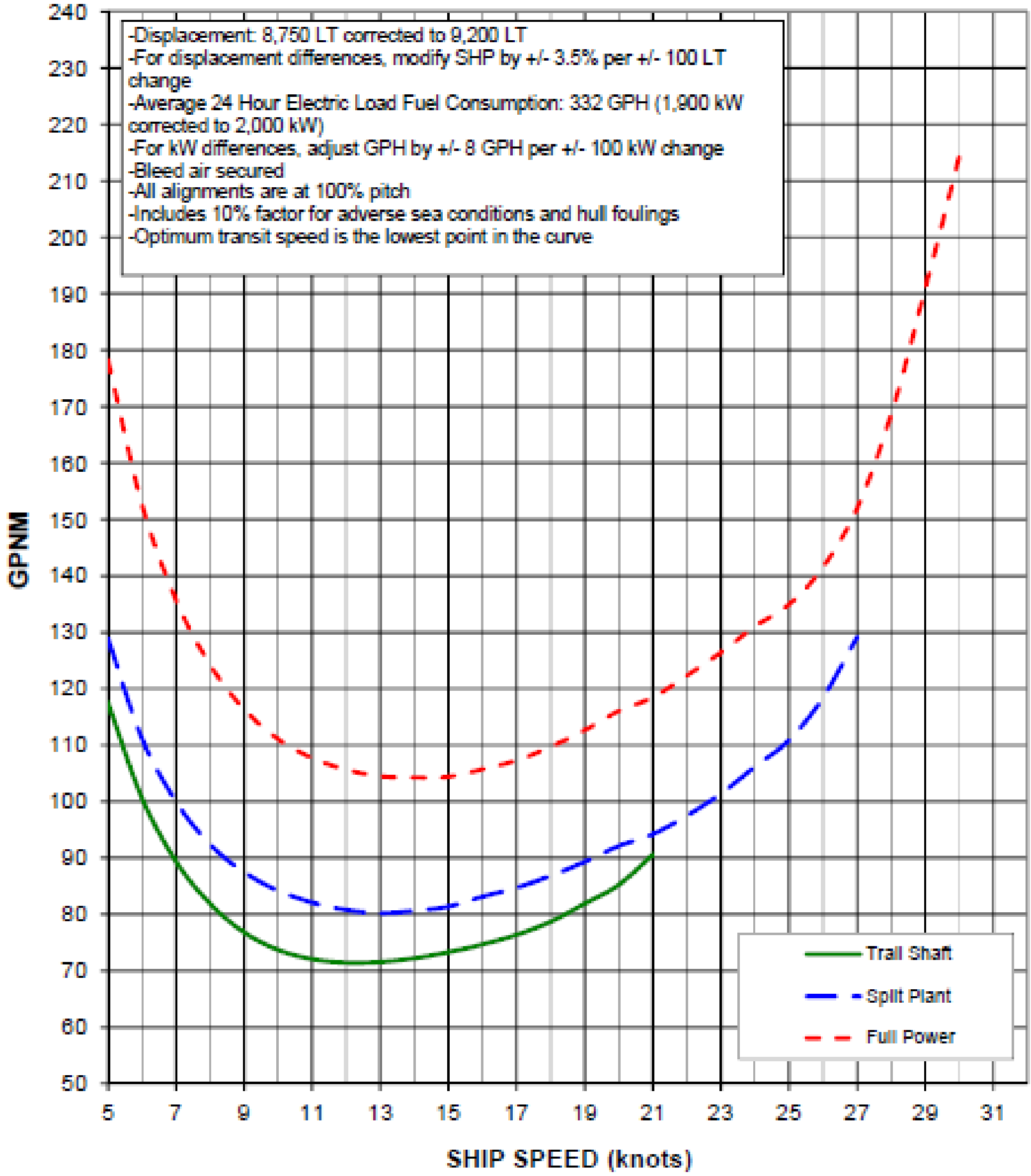
This appendix contains fuel curves for CG, DDG flight 1, DDG flight 2A, LCS1, LCS2, LHA, LHD, LSD, LPD, and FFG7 class ships.

Figure 20. CG 47 class total ship fuel consumption (with stern flap) (GPNM)



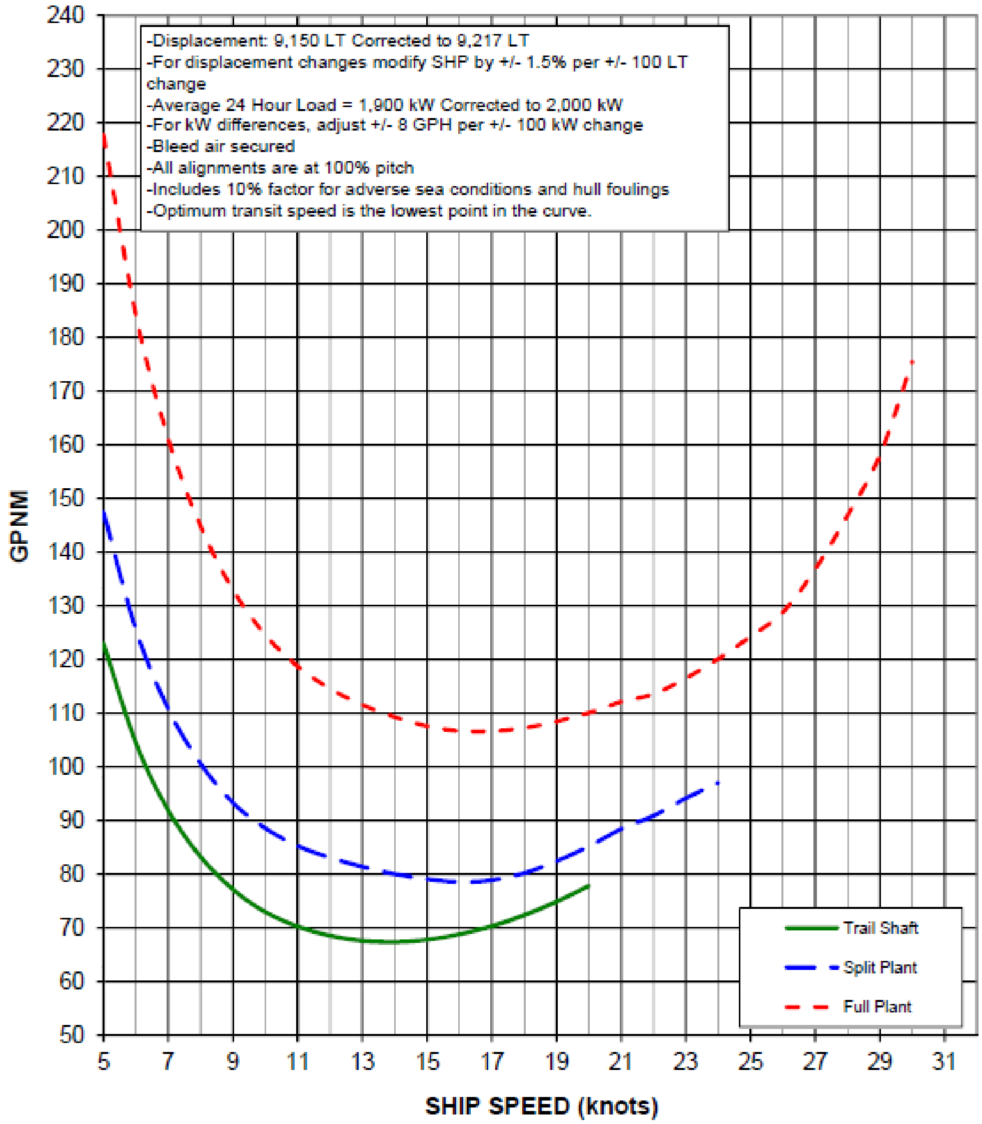
Adapted from: Hasan P (2015)

Figure 21. DDG51 FLT 1 and II class total ship fuel consumption (with stern flap) (GPNM)



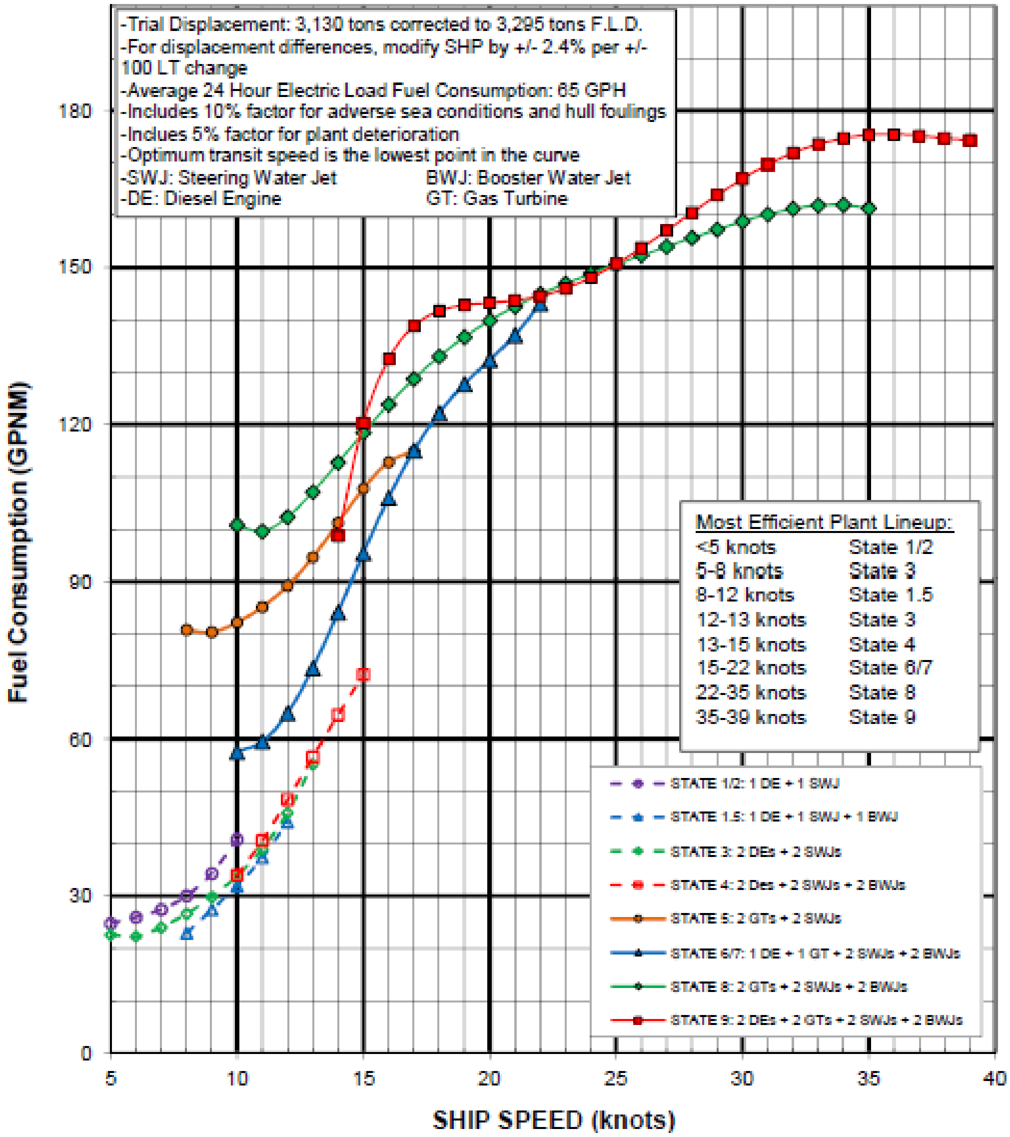
Source: Hasan P (2015)

Figure 22. DDG51 FLT IIA class total ship fuel consumption (with stern flap) (GPNM)



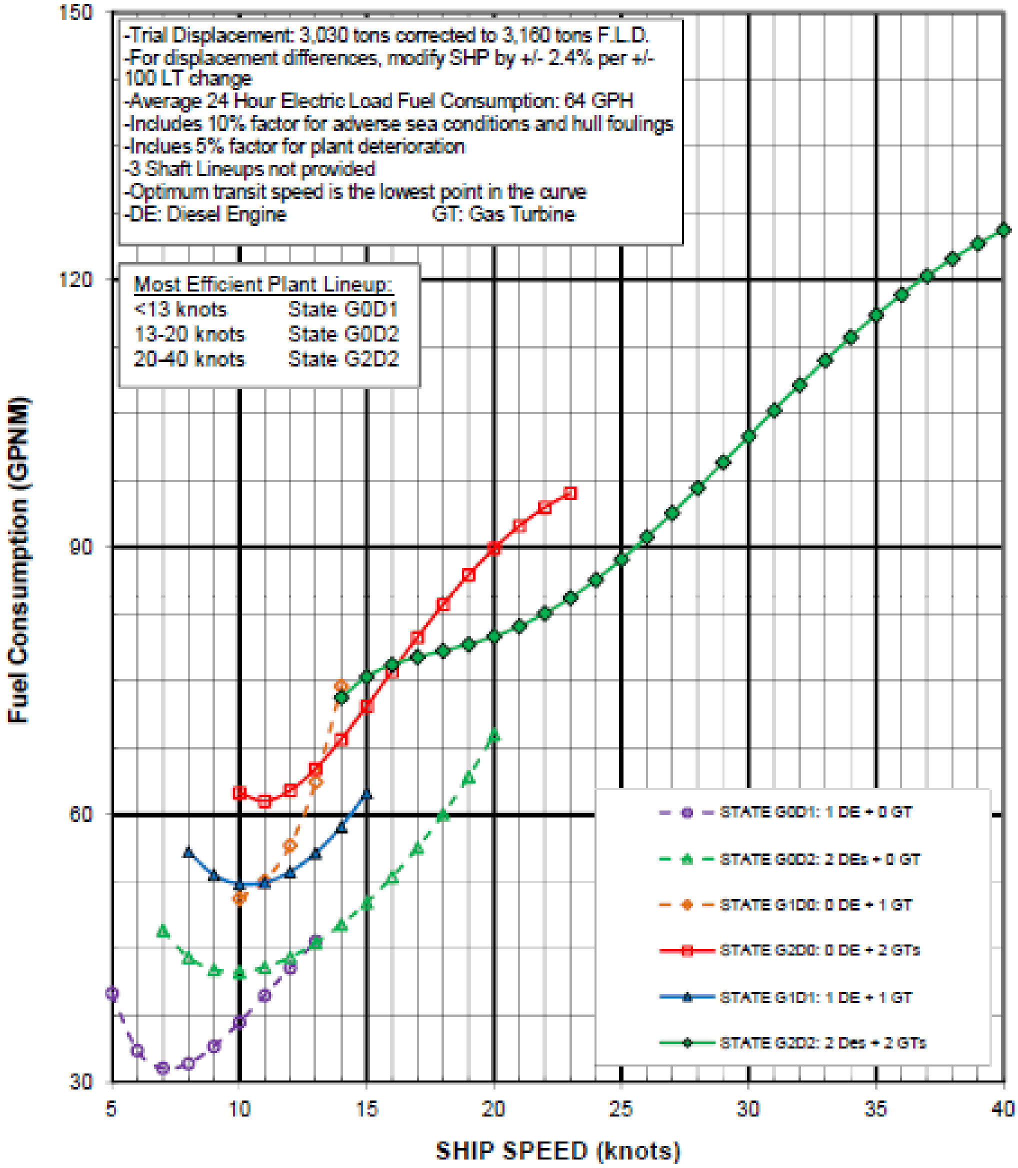
Source: Hasan P (2015)

Figure 23. LCS1 total ship fuel consumption (GPNM)



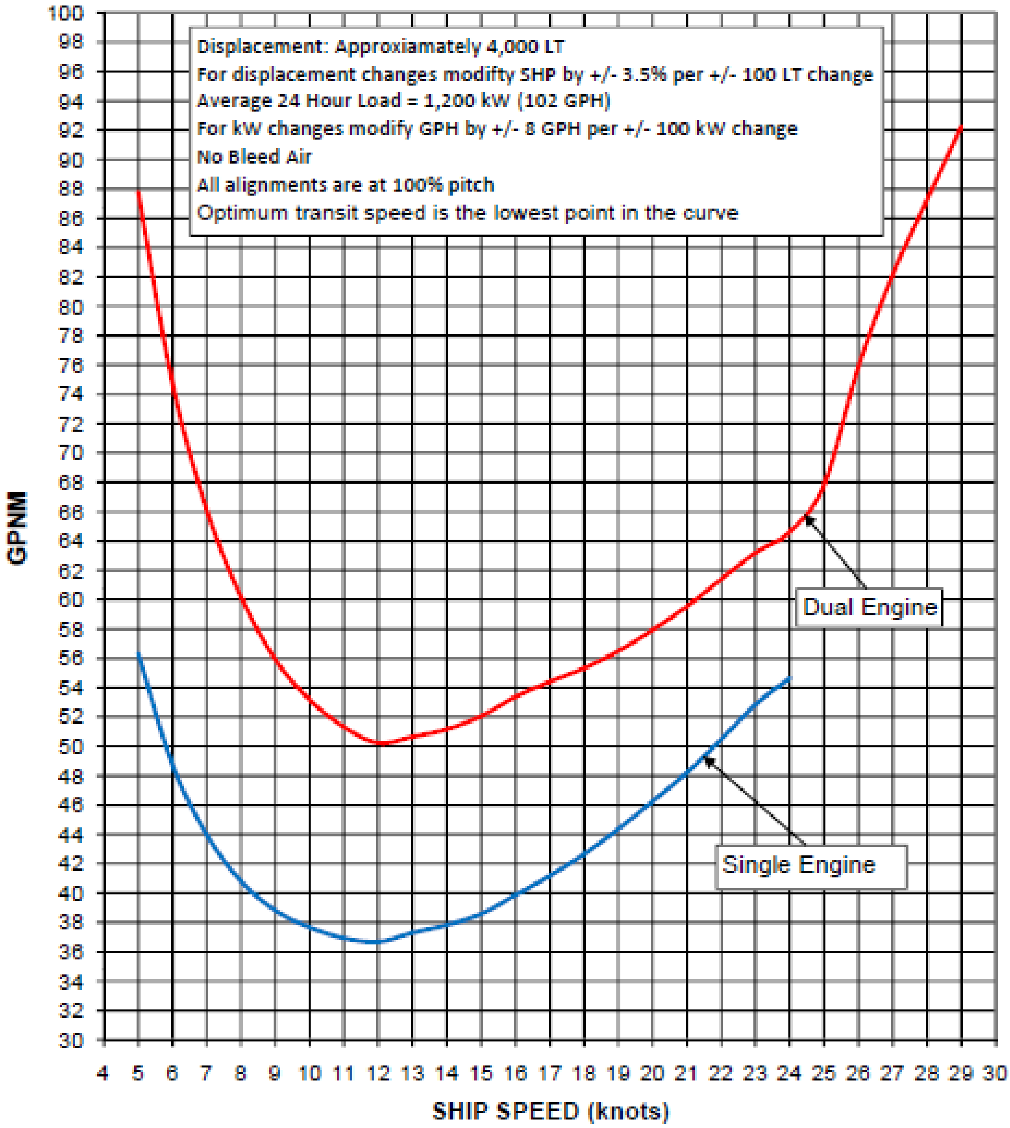
Source: Hasan P (2015)

Figure 24. LCS2 total ship fuel consumption (GPNM)



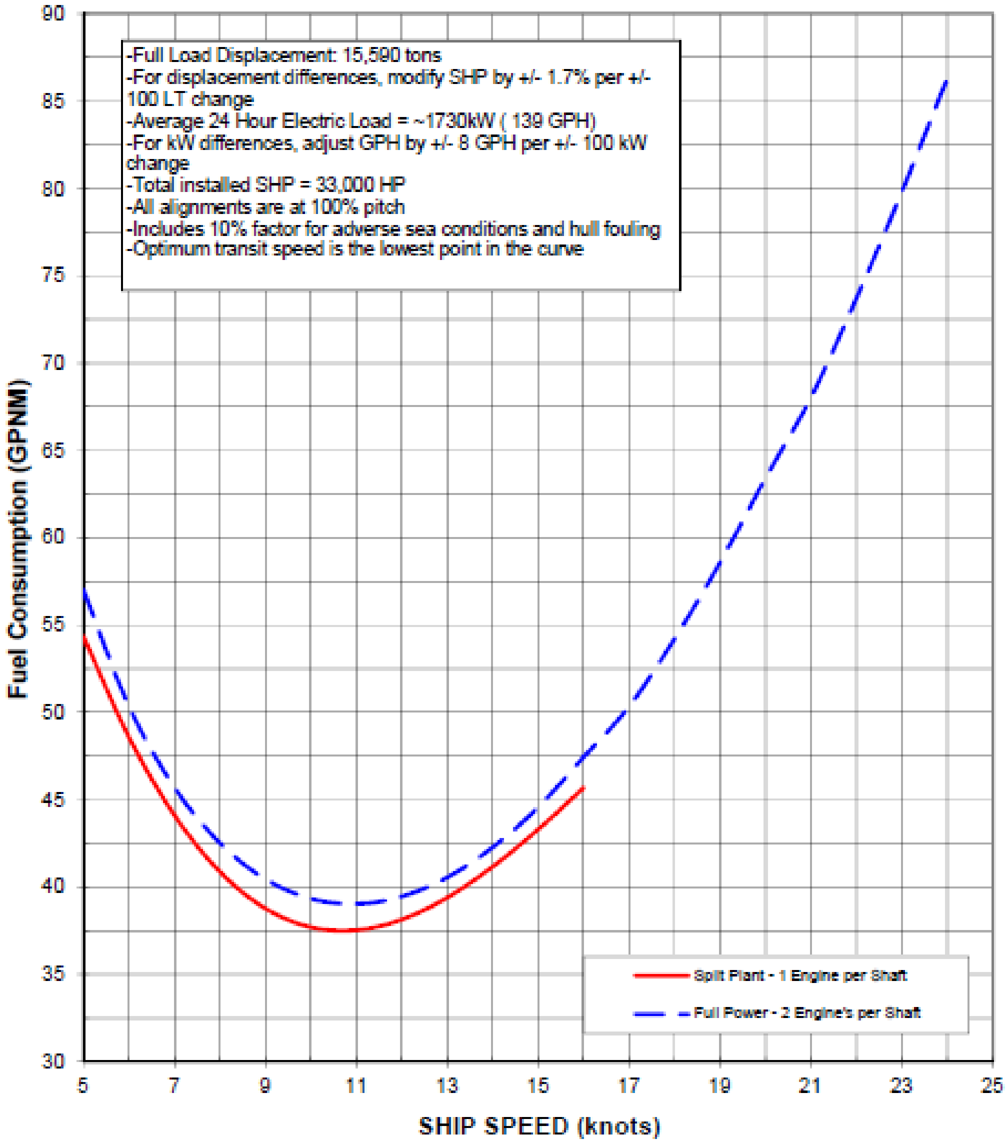
Source: Hasan P (2015)

Figure 25. FFG7 class total ship fuel consumption (with stern flap) (GPNM)



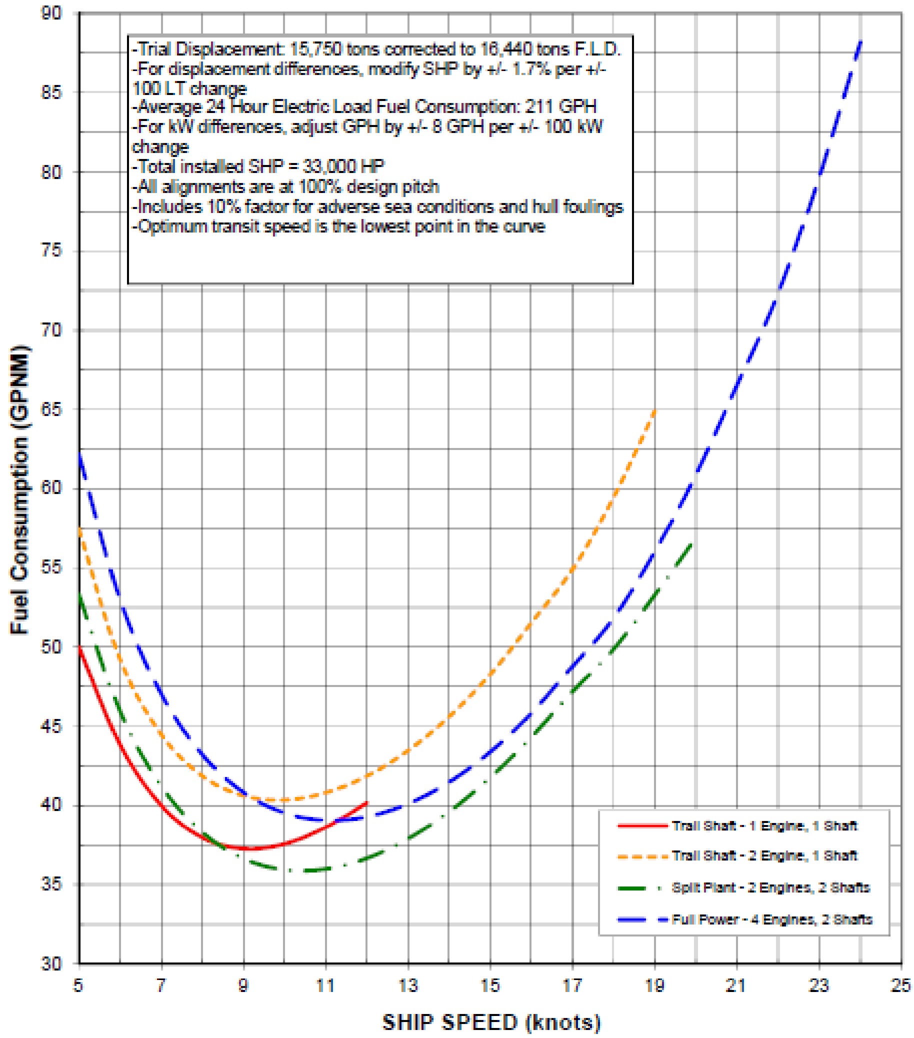
Source: Hasan P (2015)

Figure 26. LSD41 class total ship fuel consumption (GPNM)



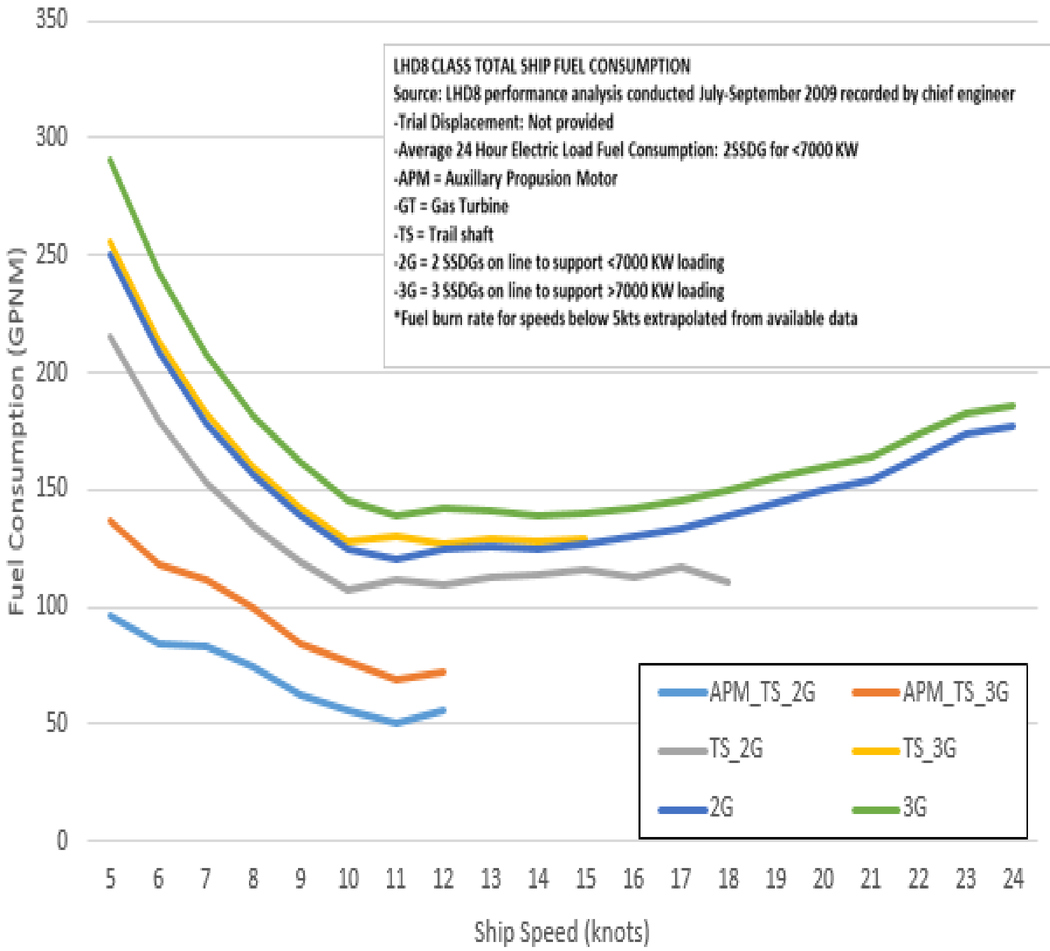
Source: Hasan P (2015)

Figure 27. LSD49 class total ship fuel consumption (GPNM)



Source: Hasan P (2015)

Figure 28. LHD8 class total ship fuel consumption (GPNM)



Adapted from Pehlivan H (2015)

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B. OTTER STATIC TOOLS

This appendix contains OTTER static tools for CG, DDG flight 1, DDG flight 2A, LCS1, LCS2, LHA, LHD1, LHD8, LSD, LPD, and FFG7 class ships. Reference sheets are to be used independently with no required assumptions. Fuel performance dates for each class ship are annotated on the sheet.

Figure 29. CG Static OTTER

NAVAL POSTGRADUATE SCHOOL

CG

OTTER V1.2

Speed Table

Avg Speed	Speed 1 Speed	Speed 1 Time %	Speed 1 Mode	Hours to PIM Rear	Speed 2 Speed	Speed 2 Time %	Speed 2 Mode	Hours to PIM Front	GPH Saved
0	0	100	Drift	---				---	
1	0	75	Drift	4.00	4	25	Trail Shaft	1.33	1
2	0	50	Drift	4.00	4	50	Trail Shaft	4.00	1
3	3	100	Trail Shaft						
4	4	100	Trail Shaft						
5	5	100	Trail Shaft						
6	6	100	Trail Shaft						
7	7	100	Trail Shaft						
8	8	100	Trail Shaft						
9	9	100	Trail Shaft						
10	10	100	Trail Shaft						
11	10	80	Trail Shaft	44.00	15	20	Trail Shaft	11.00	1
12	10	60	Trail Shaft	24.00	15	40	Trail Shaft	16.00	3
13	10	40	Trail Shaft	17.33	15	60	Trail Shaft	26.00	2
14	14	100	Trail Shaft						
15	15	100	Trail Shaft						
16	16	100	Trail Shaft						
17	17	100	Trail Shaft						
18	18	100	Trail Shaft						
19	19	100	Trail Shaft						
20	20	100	Trail Shaft						
21	20	67	Trail Shaft	84.00	23	33	Split Plant	42.00	129
22	20	33	Trail Shaft	44.00	23	67	Split Plant	88.00	56
23	23	100	Split Plant						
24	23	80	Split Plant	96.00	28	20	Full Power	24.00	320
25	23	60	Split Plant	50.00	28	40	Full Power	33.33	202
26	23	40	Split Plant	34.67	28	60	Full Power	52.00	92
27	23	20	Split Plant	27.00	28	80	Full Power	108.00	11
28	28	100	Full Power						
29	29	100	Full Power						
30	30	100	Full Power						
31									
32									
33									
34									
35									
36									
37									
38									
39									
40									

NAVAL POSTGRADUATE SCHOOL

CG

OTTER V1.2

Supplemental Info

CG 47 CLASS TOTAL SHIP FUEL CONSUMPTION
(With Stern Flap)
Source: USS Vincennes (CG 49) Performance and Special Trials Preliminary Results Dated January 1986
Source: USS Vincennes (CG 49) Fuel Performance Trials Final Report, Project PM 5346 Dated November 1985
Displacement = 9,545 LT from report Dated November 1985
For displacement changes modify SHP by +/- 3.5% per +/- 100 LT change
Average 24-Hour Load = 2,200 kW (388 GPH) from Fuel Performance Trials Final Report
For kW changes modify GPH by +/- 8 GPH per +/- 100 kW change
No Bleed Air

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always

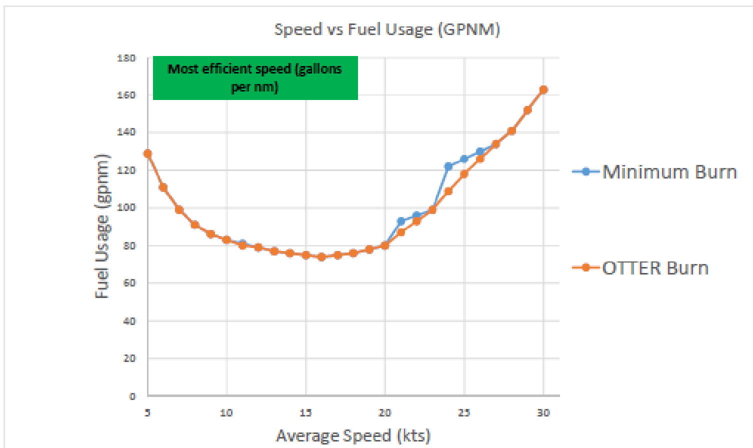


Figure 30. DDG1 Static OTTER

NAVAL POSTGRADUATE SCHOOL

DDG1

OTTER V1.2

Speed Table

Avg Speed	Speed 1			Hours to PIM Rear	Speed 2			Hours to PIM Front	GPH Saved
	Speed	Time %	Mode		Speed	Time %	Mode		
0	0	100	Drift	---				---	
1	0	89	Drift	4.00	9	11	Trail Shaft	0.50	152
2	0	78	Drift	4.00	9	22	Trail Shaft	1.14	128
3	0	67	Drift	4.00	9	33	Trail Shaft	2.00	105
4	0	56	Drift	4.00	9	44	Trail Shaft	3.20	82
5	0	44	Drift	4.00	9	56	Trail Shaft	5.00	59
6	0	33	Drift	4.00	9	67	Trail Shaft	8.00	35
7	0	22	Drift	4.00	9	78	Trail Shaft	14.00	17
8	0	11	Drift	4.00	9	89	Trail Shaft	32.00	5
9	9	100	Trail Shaft						
10	10	100	Trail Shaft						
11	11	100	Trail Shaft						
12	12	100	Trail Shaft						
13	13	100	Trail Shaft						
14	14	100	Trail Shaft						
15	15	100	Trail Shaft						
16	16	100	Trail Shaft						
17	17	100	Trail Shaft						
18	18	100	Trail Shaft						
19	19	100	Trail Shaft						
20	20	100	Trail Shaft						
21	21	100	Trail Shaft						
22	21	50	Trail Shaft	88.00	23	50	Split Plant	88.00	28
23	23	100	Split Plant						
24	24	100	Split Plant						
25	25	100	Split Plant						
26	26	100	Split Plant						
27	27	100	Split Plant						
28	27	67	Split Plant	112.00	30	33	Full Power	56.00	253
29	27	33	Split Plant	58.00	30	67	Full Power	116.00	86
30	30	100	Full Power						
31									
32									
33									
34									
35									
36									
37									
38									
39									
40									

NAVAL POSTGRADUATE SCHOOL

DDG1

OTTER V1.2

Supplemental Info

DDG 51 (FLT I & II) CLASS TOTAL SHIP FUEL CONSUMPTION

Source: USS Barry (DDG 52) ATD Fuel Performance Trail, NSWCCD letter 9234 SER 9333/062 Dated: 01 MARCH 1995 Split Plant and Full Power data taken from "Stern Flap Installation and Performance Evaluation on USS RAMAGE (DDG 61) Dated September 2001, (NSWCCD-50-TR--2001/010)
-Trial Displacement: 9,200 LT corrected from the original 8,750 LT from NAVSEA SECAT Report aboard USS McFAUL (DDG 74) dated Feb 1999
-For displacement differences, modify SHP by +/- 3.5% per +/- 100 LT change
-Average 24 Hour Electric Load Fuel Consumption: 1,900 kW (324 GPH) from NAVSEA SECAT report aboard USS McFAUL (DDG 74)

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always

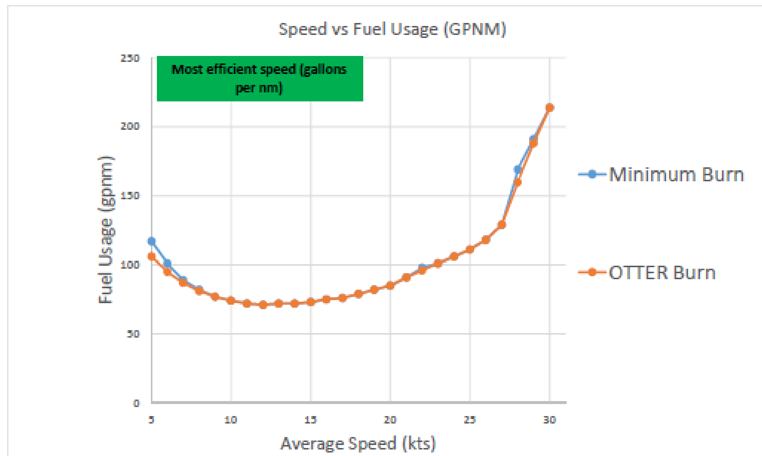


Figure 31. DDG2 Static OTTER

NAVAL POSTGRADUATE SCHOOL

DDG2A

OTTER V1.2

Speed Table

Avg Speed	Speed 1			Hours to PIM Rear	Speed 2			Hours to PIM Front	GPH Saved
	Speed	Time %	Mode		Speed	Time %	Mode		
0	0	100	Drift	---				---	
1	1	100	Trail Shaft						
2	2	100	Trail Shaft						
3	1	50	Trail Shaft	6.00	5	50	Trail Shaft	6.00	1
4	1	25	Trail Shaft	5.33	5	75	Trail Shaft	16.00	2
5	5	100	Trail Shaft						
6	6	100	Trail Shaft						
7	7	100	Trail Shaft						
8	8	100	Trail Shaft						
9	9	100	Trail Shaft						
10	10	100	Trail Shaft						
11	11	100	Trail Shaft						
12	12	100	Trail Shaft						
13	13	100	Trail Shaft						
14	14	100	Trail Shaft						
15	15	100	Trail Shaft						
16	16	100	Trail Shaft						
17	17	100	Trail Shaft						
18	18	100	Trail Shaft						
19	19	100	Trail Shaft						
20	20	100	Trail Shaft						
21	20	75	Trail Shaft	84.00	24	25	Split Plant	28.00	108
22	20	50	Trail Shaft	44.00	24	50	Split Plant	44.00	58
23	20	25	Trail Shaft	30.67	24	75	Split Plant	92.00	31
24	24	100	Split Plant						
25	24	75	Split Plant	100.00	28	25	Full Power	33.33	334
26	24	50	Split Plant	52.00	28	50	Full Power	52.00	130
27	24	25	Split Plant	36.00	28	75	Full Power	108.00	28
28	28	100	Full Power						
29	29	100	Full Power						
30	30	100	Full Power						
31									
32									
33									
34									
35									
36									
37									
38									
39									
40									

NAVAL POSTGRADUATE SCHOOL

DDG2A

OTTER V1.2

Supplemental Info

DDG 51 (FLT IIA) CLASS TOTAL SHIP FUEL CONSUMPTION
Source: Final Report USS Oscar Austin (DDG 79) Performance and Special Trials Results, dated SEPTEMBER 2001, NSWCCD-50-TR-2001-040
-Trial Displacement: 9,150 LT
-Full Load Displacement: 9,216 LT
-For displacement differences, modify SHP by +/- 0.6% per +/- 100 LT change
-Average 24 Hour Electric Load Fuel Consumption: 1,900 kW
-For kW differences, adjust GPH by +/- 8 GPH per +/- 100 kW change
-Bleed Air Secured
-Total installed SHP = 100,000 HP

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always

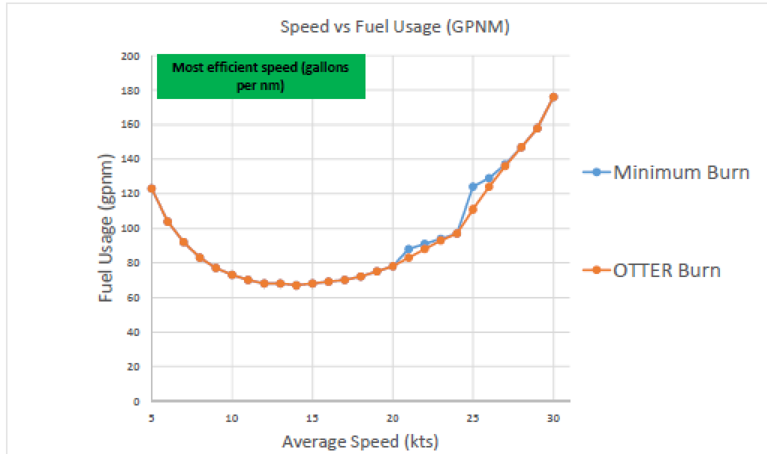


Figure 32. LCS1 Static OTTER

NAVAL POSTGRADUATE SCHOOL

LCS1

OTTER V1.2

Speed Table

Avg Speed	Speed 1: Speed	Speed 1: Time %	Speed 1: Mode	Hours to PIM Rear	Speed 2: Speed	Speed 2: Time %	Speed 2: Mode	Hours to PIM Front	GPH Saved
0	0	100	Drift	---				---	
1	0	80	Drift	4.00	5	20	State 3	1.00	38
2	0	60	Drift	4.00	5	40	State 3	2.67	29
3	0	40	Drift	4.00	5	60	State 3	6.00	19
4	0	20	Drift	4.00	5	80	State 3	16.00	10
5	5	100	State 3						
6	6	100	State 3						
7	6	50	State 3	28.00	8	50	State 1.5	28.00	9
8	8	100	State 1.5						
9	9	100	State 1.5						
10	10	100	State 1.5						
11	11	100	State 1.5						
12	12	100	State 1.5						
13	12	67	State 1.5	52.00	15	33	State 4	26.00	2
14	12	33	State 1.5	28.00	15	67	State 4	56.00	5
15	15	100	State 4						
16	15	95	State 4	64.00	35	5	State 8	3.37	384
17	15	90	State 4	34.00	35	10	State 8	3.78	414
18	15	85	State 4	24.00	35	15	State 8	4.24	432
19	15	80	State 4	19.00	35	20	State 8	4.75	432
20	15	75	State 4	16.00	35	25	State 8	5.33	422
21	15	70	State 4	14.00	35	30	State 8	6.00	426
22	15	65	State 4	12.57	35	35	State 8	6.77	468
23	15	60	State 4	11.50	35	40	State 8	7.67	449
24	15	55	State 4	10.67	35	45	State 8	8.73	417
25	15	50	State 4	10.00	35	50	State 8	10.00	400
26	15	45	State 4	9.45	35	55	State 8	11.56	367
27	15	40	State 4	9.00	35	60	State 8	13.50	337
28	15	35	State 4	8.62	35	65	State 8	16.00	310
29	15	30	State 4	8.29	35	70	State 8	19.33	284
30	15	25	State 4	8.00	35	75	State 8	24.00	258
31	15	20	State 4	7.75	35	80	State 8	31.00	231
32	15	15	State 4	7.53	35	85	State 8	42.67	197
33	15	10	State 4	7.33	35	90	State 8	66.00	152
34	15	5	State 4	7.16	35	95	State 8	136.00	89
35	35	100	State 8						
36	35	75	State 8	144.00	39	25	State 9	48.00	381
37	35	50	State 8	74.00	39	50	State 9	74.00	259
38	35	25	State 8	50.67	39	75	State 9	152.00	129
39	39	100	State 9						
40									

NAVAL POSTGRADUATE SCHOOL

LCS1

OTTER V1.2

Supplemental Info

LCS 1 CLASS TOTAL SHIP FUEL CONSUMPTION

Source: NSWCCD-50-TR-2012/016, "USS Freedom (LCS 1) Performance and Special Trials Results Volume 1." Dated April 2012

-Trial Displacement: 3,130 tons corrected to 3,295 tons Full Load Displacement

-For displacement differences, modify SHP by +/- 2.4% per +/- 100 LT change

-Average 24 Hour Electric Load Fuel Consumption: 65 GPH

-Includes 10% factor for adverse sea conditions and hull foulings

-Includes 5% factor for plant deterioration

-SWJ = Steering Water Jet; BWJ = Booster Water Jet

-GT = Gas Turbine; DE = Diesel Engine

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always

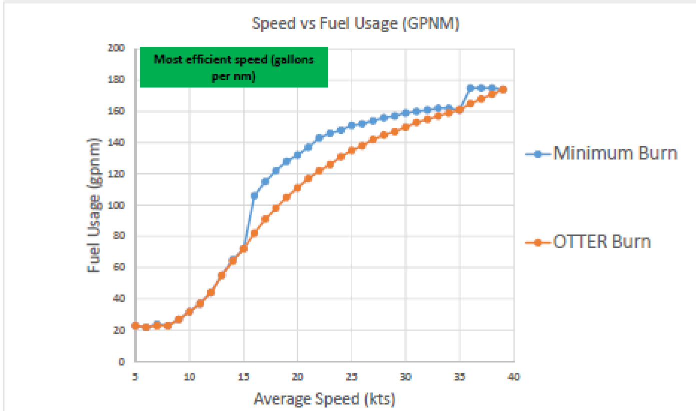


Figure 33. LCS2 Static OTTER

NAVAL POSTGRADUATE SCHOOL

LCS2

OTTER V1.2

Speed Table

Avg Speed	Speed 1			Hours to PIM Rear	Speed 2			Hours to PIM Front	GPH Saved
	Speed	Time %	Mode		Speed	Time %	Mode		
0	0	100	Drift	---				---	
1	0	86	Drift	4.00	7	14	G0D1	0.67	114
2	0	71	Drift	4.00	7	29	G0D1	1.60	91
3	0	57	Drift	4.00	7	43	G0D1	3.00	69
4	0	43	Drift	4.00	7	57	G0D1	5.33	46
5	0	29	Drift	4.00	7	71	G0D1	10.00	24
6	0	14	Drift	4.00	7	86	G0D1	24.00	2
7	7	100	G0D1						
8	8	100	G0D1						
9	9	100	G0D1						
10	10	100	G0D1						
11	11	100	G0D1						
12	12	100	G0D1						
13	11	33	G0D1	26.00	14	67	G0D2	52.00	2
14	14	100	G0D2						
15	15	100	G0D2						
16	16	100	G0D2						
17	17	100	G0D2						
18	18	100	G0D2						
19	19	100	G0D2						
20	20	100	G0D2						
21	20	86	G0D2	84.00	27	14	G2D2	14.00	159
22	20	71	G0D2	44.00	27	29	G2D2	17.60	107
23	20	57	G0D2	30.67	27	43	G2D2	23.00	65
24	20	43	G0D2	24.00	27	57	G2D2	32.00	34
25	20	29	G0D2	20.00	27	71	G2D2	50.00	12
26	20	14	G0D2	17.33	27	86	G2D2	104.00	1
27	27	100	G2D2						
28	28	100	G2D2						
29	29	100	G2D2						
30	30	100	G2D2						
31	31	100	G2D2						
32	31	89	G2D2	128.00	40	11	G2D2	16.00	2
33	31	78	G2D2	66.00	40	22	G2D2	18.86	6
34	31	67	G2D2	45.33	40	33	G2D2	22.67	10
35	31	56	G2D2	35.00	40	44	G2D2	28.00	15
36	31	44	G2D2	28.80	40	56	G2D2	36.00	18
37	31	33	G2D2	24.67	40	67	G2D2	49.33	20
38	31	22	G2D2	21.71	40	78	G2D2	76.00	17
39	31	11	G2D2	19.50	40	89	G2D2	156.00	11
40	40	100	G2D2						

NAVAL POSTGRADUATE SCHOOL

LCS2

OTTER V1.2

Supplemental Info

LCS 2 CLASS TOTAL SHIP FUEL CONSUMPTION
Source: NSWCCD-80-TR-2014/031, "USS Independence (LCS 2) Performance and Special Trials Calm Water Trials," Dated August 2014
-Trial Displacement: 3,030 tons corrected to 3,160 tons Full Load Displacement
-For displacement differences, modify SHP by +/- 2.4% per +/- 100 LT change
-Average 24 Hour Electric Load Fuel Consumption: 64 GPH
-Includes 10% factor for adverse sea conditions and hull foulings
-Includes 5% factor for plant deterioration
-3 Shaft Alignments not included - G2D1 tested at 29 knots and fuel consumption was greater than G2D2
***Fuel burn rate for speeds below 5kts extrapolated from available data**

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always

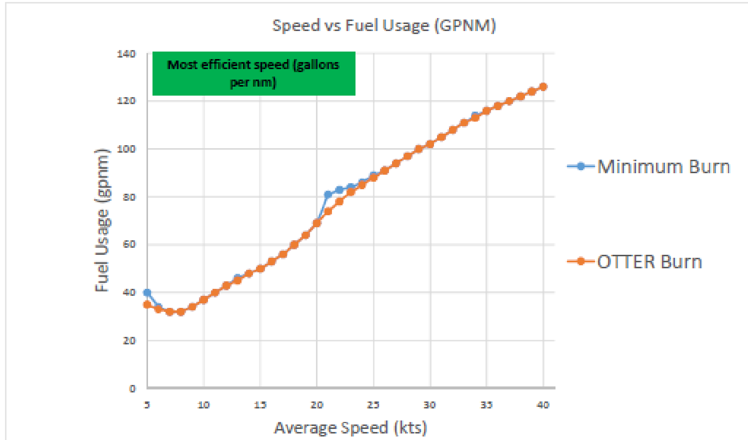


Figure 34. LHA1 Static OTTER

NAVAL POSTGRADUATE SCHOOL

LHA1 — **OTTER V1.2** — Speed Table

Avg Speed	Speed 1: Speed	Speed 1: Time %	Speed 1: Mode	Hours to PIM Rear	Speed 2: Speed	Speed 2: Time %	Speed 2: Mode	Hours to PIM Front	GPH Saved
0	0	100	Drift	---				---	
1	0	80	Drift	4.00	5	20	SBXC	1.00	4
2	0	60	Drift	4.00	5	40	SBXC	2.67	3
3	0	40	Drift	4.00	5	60	SBXC	6.00	2
4	0	20	Drift	4.00	5	80	SBXC	16.00	1
5	5	100	SBXC						
6	6	100	SBXC						
7	7	100	SBXC						
8	8	100	SBXC						
9	9	100	SBXC						
10	10	100	SBXC						
11	11	100	SBXC						
12	12	100	SBXC						
13	13	100	SBXC						
14	14	100	SBXC						
15	15	100	SBXC						
16	16	100	SBXC						
17	17	100	SBXC						
18	18	100	SBXC						
19	19	100	SBXC						
20	20	100	2BSplit						
21	21	100	2BSplit						
22	22	100	2BSplit						
23	23	100	2BSplit						
24	24	100	2BSplit						
25									
26									
27									
28									
29									
30									
31									
32									
33									
34									
35									
36									
37									
38									
39									
40									

NAVAL POSTGRADUATE SCHOOL

LHA1 — **OTTER V1.2** — Supplemental Info

LHA 1 CLASS TOTAL SHIP FUEL CONSUMPTION
Source (1): David W. Taylor Naval Ship Research and Development Center Report # 77-0008 "Standardization and Preliminary Fuel Economy Trials of USS Tarawa (LHA 1), Donald H. Drazin. Dated January 1977
Source (2): NAVSECPHILADIV Project B-1533, "USS Tarawa (LHA-1) NAVSEA Performance and Special Trials Fuel Economy Trials Report" Dated 5 May 1977
-Trial displacement: 39,400 tons corrected to 38,900 tons F.L.D.
-For displacement differences, modify SHP by +/- 0.4% per +/- 100 LT change
-Total installed SHP = 70,000 HP
-All alignments are at 100% design pitch

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always

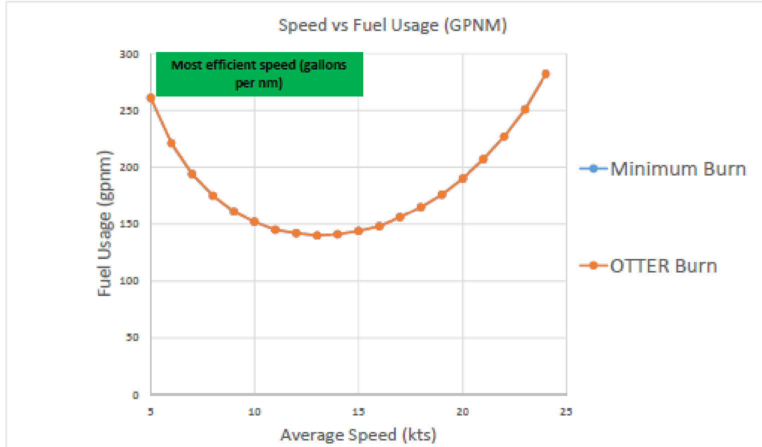


Figure 35. LHD1 Static OTTER

NAVAL POSTGRADUATE SCHOOL

LHD1

OTTER V1.2

Speed Table

Avg Speed	Speed 1			Hours to PIM Rear	Speed 2			Hours to PIM Front	GPH Saved
	Speed	Time %	Mode		Speed	Time %	Mode		
0	0	100	Drift	---				---	
1	0	88	Drift	4.00	8	13	SBEcon	0.57	9
2	0	75	Drift	4.00	8	25	SBEcon	1.33	7
3	0	63	Drift	4.00	8	38	SBEcon	2.40	6
4	0	50	Drift	4.00	8	50	SBEcon	4.00	5
5	0	38	Drift	4.00	8	63	SBEcon	6.67	4
6	0	25	Drift	4.00	8	75	SBEcon	12.00	2
7	0	13	Drift	4.00	8	88	SBEcon	28.00	1
8	8	100	SBEcon						
9	8	75	SBEcon	36.00	12	25	SBEcon	12.00	5
10	8	50	SBEcon	20.00	12	50	SBEcon	20.00	10
11	8	25	SBEcon	14.67	12	75	SBEcon	44.00	5
12	12	100	SBEcon						
13	13	100	SBEcon						
14	12	33	SBEcon	28.00	15	67	SBEcon	56.00	1
15	15	100	SBEcon						
16	16	100	SBEcon						
17	17	100	SBEcon						
18	18	100	SBEcon						
19	19	100	SBEcon						
20	20	100	SBEcon						
21	20	80	SBEcon	84.00	25	20	2BEcon	21.00	75
22	22	100	2BEcon						
23	23	100	2BEcon						
24	24	100	2BEcon						
25	25	100	2BEcon						
26									
27									
28									
29									
30									
31									
32									
33									
34									
35									
36									
37									
38									
39									
40									

NAVAL POSTGRADUATE SCHOOL

LHD1

OTTER V1.2

Supplemental Info

LHD 1 CLASS TOTAL SHIP FUEL CONSUMPTION
Source: NAVSEA iENCON SECAT XL Version 1.2 Class Trial Data (From LHD 2 USS ESSEX)
-Ship Displacement, LT = 41,250
-Average 24 Hour Electric Load: 3350 kW
-All alignments are at 100% design pitch
-SBEcon = single boiler economic
-2BEcon = 2 boiler economic
-2BFull = 2 boiler full power
***Fuel burn rate for speeds below 5kts extrapolated from available data**

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always

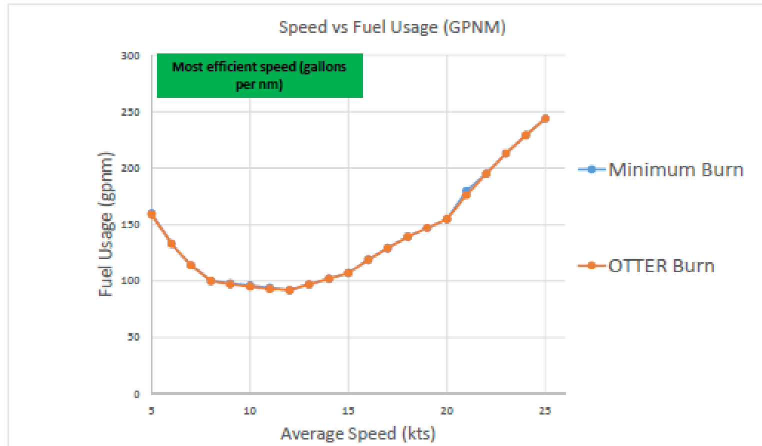


Figure 36. LPD4 Static OTTER

NAVAL POSTGRADUATE SCHOOL

LPD4

OTTER V1.2

Speed Table

Avg Speed	Speed 1			Hours to PIM Rear	Speed 2			Hours to PIM Front	GPH Saved
	Speed	Time %	Mode		Speed	Time %	Mode		
0	0	100	Drift	---				---	
1	0	83	Drift	4.00	6	17	SBEcon	0.80	8
2	0	67	Drift	4.00	6	33	SBEcon	2.00	7
3	0	50	Drift	4.00	6	50	SBEcon	4.00	5
4	0	33	Drift	4.00	6	67	SBEcon	8.00	3
5	0	17	Drift	4.00	6	83	SBEcon	20.00	2
6	6	100	SBEcon						
7	6	75	SBEcon	28.00	10	25	SBEcon	9.33	17
8	6	50	SBEcon	16.00	10	50	SBEcon	16.00	35
9	6	25	SBEcon	12.00	10	75	SBEcon	36.00	77
10	10	100	SBEcon						
11	11	100	SBEcon						
12	12	100	SBEcon						
13	13	100	SBEcon						
14	14	100	SBEcon						
15	15	100	SBEcon						
16	15	80	SBEcon	64.00	20	20	2BEcon	16.00	85
17	15	60	SBEcon	34.00	20	40	2BEcon	22.67	60
18	15	40	SBEcon	24.00	20	60	2BEcon	36.00	34
19	15	20	SBEcon	19.00	20	80	2BEcon	76.00	17
20	20	100	2BEcon						
21									
22									
23									
24									
25									
26									
27									
28									
29									
30									
31									
32									
33									
34									
35									
36									
37									
38									
39									
40									

NAVAL POSTGRADUATE SCHOOL

LPD4

OTTER V1.2

Supplemental Info

LPD 4 CLASS TOTAL SHIP FUEL CONSUMPTION
Source: NAVSEA iENCON SECAT XL Version 1.2 Class Trial Data (From LPD 9 USS DENVER)
-Ship Displacement, LT = 15,060
-Average 24 Hour Electric Load: 800 kW
-All alignments are at 100% design pitch
-SBEcon = single boiler economic
-2BEcon = 2 boiler economic
-2BFull = 2 boiler full power
***Fuel burn rate for speeds below 5kts extrapolated from available data**

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always

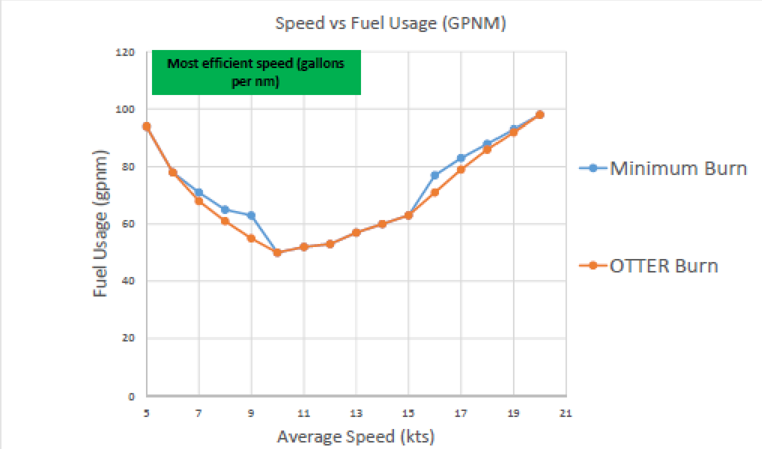


Figure 37. LSD41 Static OTTER

NAVAL POSTGRADUATE SCHOOL

LSD41

OTTER V1.2

Speed Table

Avg Speed	Speed 1 Speed	Speed 1 Time %	Speed 1 Mode	Hours to PIM Rear	Speed 2 Speed	Speed 2 Time %	Speed 2 Mode	Hours to PIM Front	GPH Saved
0	0	100	Drift	---				---	
1	0	89	Drift	4.00	9	11	Split 1E	0.50	110
2	0	78	Drift	4.00	9	22	Split 1E	1.14	86
3	0	67	Drift	4.00	9	33	Split 1E	2.00	63
4	0	56	Drift	4.00	9	44	Split 1E	3.20	40
5	0	44	Drift	4.00	9	56	Split 1E	5.00	16
6	0	33	Drift	4.00	9	67	Split 1E	8.00	12
7	0	22	Drift	4.00	9	78	Split 1E	14.00	7
8	0	11	Drift	4.00	9	89	Split 1E	32.00	1
9	9	100	Split 1E						
10	10	100	Split 1E						
11	11	100	Split 1E						
12	12	100	Split 1E						
13	13	100	Split 1E						
14	14	100	Split 1E						
15	15	100	Split 1E						
16	16	100	Split 1E						
17	16	50	Split 1E	68.00	18	50	Full 2E	68.00	2
18	18	100	Full 2E						
19	19	100	Full 2E						
20	20	100	Full 2E						
21	21	100	Full 2E						
22	22	100	Full 2E						
23	23	100	Full 2E						
24	24	100	Full 2E						
25									
26									
27									
28									
29									
30									
31									
32									
33									
34									
35									
36									
37									
38									
39									
40									

NAVAL POSTGRADUATE SCHOOL

LSD41

OTTER V1.2

Supplemental Info

LSD 41 CLASS TOTAL SHIP FUEL CONSUMPTION
Source: David Taylor Research Center Report # DTRC-SHD-1368-01 "USS RUSHMORE (LSD 47) Fuel Economy, Builder's and Acceptance Trials", Douglas Griggs and Vincent Bono. Dated October 1991
- Full Load Displacement 15,590 tons
-For displacement differences, modify SHP by +/- 1.7% per +/- 100 LT change
-Average 24 Hour Electric Load Fuel Consumption: ~1730kW (139 GPH)
-For kW differences, adjust GPH by +/- 8 GPH per +/- 100 kW change
-Total installed SHP = 33,000 HP
-All alignments are at 100% design pitch

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always

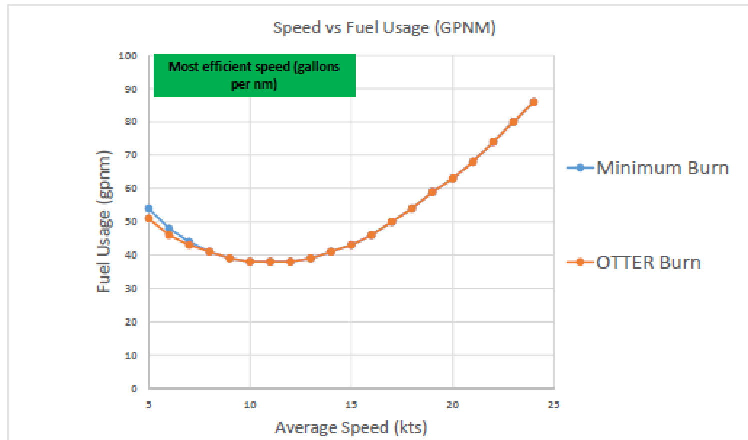


Figure 38. LSD49 Static OTTER

NAVAL POSTGRADUATE SCHOOL

LSD49

OTTER V1.2

Speed Table

Avg Speed	Speed 1: Speed	Speed 1: Time %	Speed 1: Mode	Hours to PIM Rear	Speed 2: Speed	Speed 2: Time %	Speed 2: Mode	Hours to PIM Front	GPH Saved
0	0	100	Drift	---				---	
1	0	80	Drift	4.00	5	20	Trail 1/1	1.00	31
2	0	60	Drift	4.00	5	40	Trail 1/1	2.67	23
3	0	40	Drift	4.00	5	60	Trail 1/1	6.00	16
4	0	20	Drift	4.00	5	80	Trail 1/1	16.00	8
5	5	100	Trail 1/1						
6	6	100	Trail 1/1						
7	7	100	Trail 1/1						
8	8	100	Trail 1/1						
9	9	100	Split 2/2						
10	10	100	Split 2/2						
11	11	100	Split 2/2						
12	12	100	Split 2/2						
13	13	100	Split 2/2						
14	14	100	Split 2/2						
15	15	100	Split 2/2						
16	16	100	Split 2/2						
17	17	100	Split 2/2						
18	18	100	Split 2/2						
19	19	100	Split 2/2						
20	20	100	Split 2/2						
21	20	50	Split 2/2	84.00	22	50	Full Power	84.00	33
22	22	100	Full Power						
23	23	100	Full Power						
24	24	100	Full Power						
25									
26									
27									
28									
29									
30									
31									
32									
33									
34									
35									
36									
37									
38									
39									
40									

NAVAL POSTGRADUATE SCHOOL

LSD49

OTTER V1.2

Supplemental Info

LSD 49 CLASS TOTAL SHIP FUEL CONSUMPTION
Source: NSWCCD-50-TR-2000/02, "LSD 49 Cargo Variant Class Standardization, Fuel Economy, Tactical and Maneuvering Trials as measured on USS Carter Hall (LSD 50) and USS Oak Hill (LSD 51)." Dated 25 Aug 1993
-Trial Displacement: 15,750 tons corrected to 16,440 tons Full Load Displacement
-For displacement differences, modify SHP by +/- 1.7% per +/- 100 LT change
-Average 24 Hour Electric Load Fuel Consumption: 211 GPH
-For kW differences, adjust GPH by +/- 8 GPH per +/- 100 kW change
-Total installed SHP = 33,000 HP
-All alignments are at 100% design pitch

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always

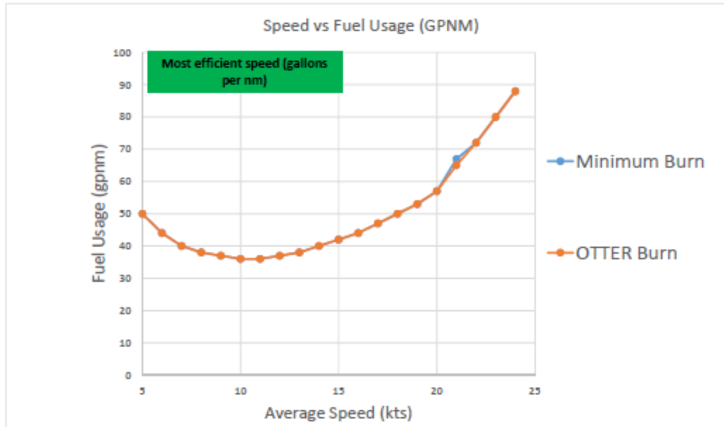


Figure 39. LHD8 Static OTTER

NAVAL POSTGRADUATE SCHOOL

LHD8 **OTTER V1.2**

Speed Table

Avg Speed	Speed 1			Hours to PIM Rear	Speed 2			Hours to PIM Front	GPH Saved
	Speed	Time %	Mode		Speed	Time %	Mode		
0	0	100	Drift	---				---	
1	0	91	Drift	4.00	11	9	APM_2G	0.40	31
2	0	82	Drift	4.00	11	18	APM_2G	0.89	27
3	0	73	Drift	4.00	11	27	APM_2G	1.50	23
4	0	64	Drift	4.00	11	36	APM_2G	2.29	19
5	0	55	Drift	4.00	11	45	APM_2G	3.33	5
6	0	45	Drift	4.00	11	55	APM_2G	4.80	15
7	0	36	Drift	4.00	11	64	APM_2G	7.00	76
8	0	27	Drift	4.00	11	73	APM_2G	10.67	77
9	0	18	Drift	4.00	11	82	APM_2G	18.00	28
10	0	9	Drift	4.00	11	91	APM_2G	40.00	14
11	11	100	APM_2G						
12	12	100	APM_2G						
13	12	83	APM_2G	52.00	18	17	GT_TS_2G	10.40	578
14	12	67	APM_2G	28.00	18	33	GT_TS_2G	14.00	477
15	12	50	APM_2G	20.00	18	50	GT_TS_2G	20.00	405
16	12	33	APM_2G	16.00	18	67	GT_TS_2G	32.00	243
17	12	17	APM_2G	13.60	18	83	GT_TS_2G	68.00	212
18	18	100	GT_TS_2G						
19	18	83	GT_TS_2G	76.00	24	17	GT_2G	15.20	375
20	18	67	GT_TS_2G	40.00	24	33	GT_2G	20.00	250
21	18	50	GT_TS_2G	28.00	24	50	GT_2G	28.00	125
22	18	33	GT_TS_2G	22.00	24	67	GT_2G	44.00	120
23	18	17	GT_TS_2G	18.40	24	83	GT_2G	92.00	125
24	24	100	GT_2G						
25									
26									
27									
28									
29									
30									
31									
32									
33									
34									
35									
36									
37									
38									
39									
40									

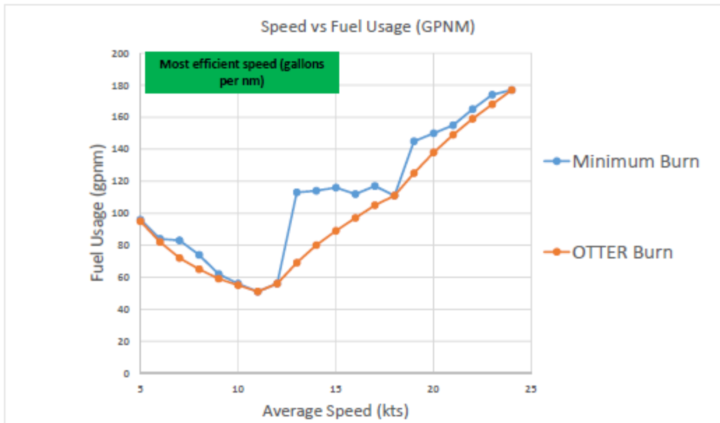
NAVAL POSTGRADUATE SCHOOL

LHD8 **OTTER V1.2**

Supplemental Info

LHD8 CLASS TOTAL SHIP FUEL CONSUMPTION
Source: LHD8 performance analysis conducted July-September 2009 recorded by chief engineer
-Trial Displacement: Not provided
-Average 24 Hour Electric Load Fuel Consumption: 2SSDG for <7000 KW
-APM = Auxillary Propusion Motor
-GT = Gas Turbine
-TS = Trail shaft
-2G = 2 SSDGs on line to support <7000 KW loading
-3G = 3 SSDGs on line to support >7000 KW loading
***Fuel burn rate for speeds below 5kts extrapolated from available data**

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always



APPENDIX C. TTSC ANALYSIS

This appendix contains histograms of the frequency and duration of TTSC of analyzed ships. Each figure contains the range of TTSC across the entire speed range of the ship. Figure 40 for example shows TTSC calculated for a CG from 1 kts average speed to 30 kts average speed in units of hours. In most instances, the CG could operate for more than 100 hours before requiring to change speed or mode. For example, a CG in transit with an average speed of 21 kts would reach the front of the operating window in

- ($BigT* \, PT_{lo,v}$)=TTSC
- (126hrs*.67)=84 hrs

Figure 40. CG TTSC

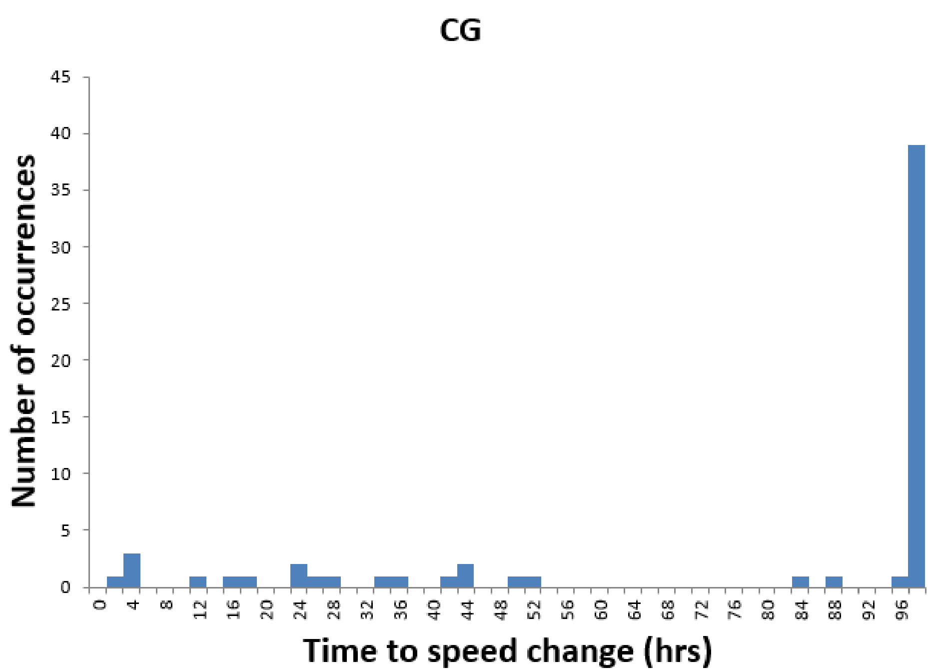


Figure 41. DDG1 TTSC

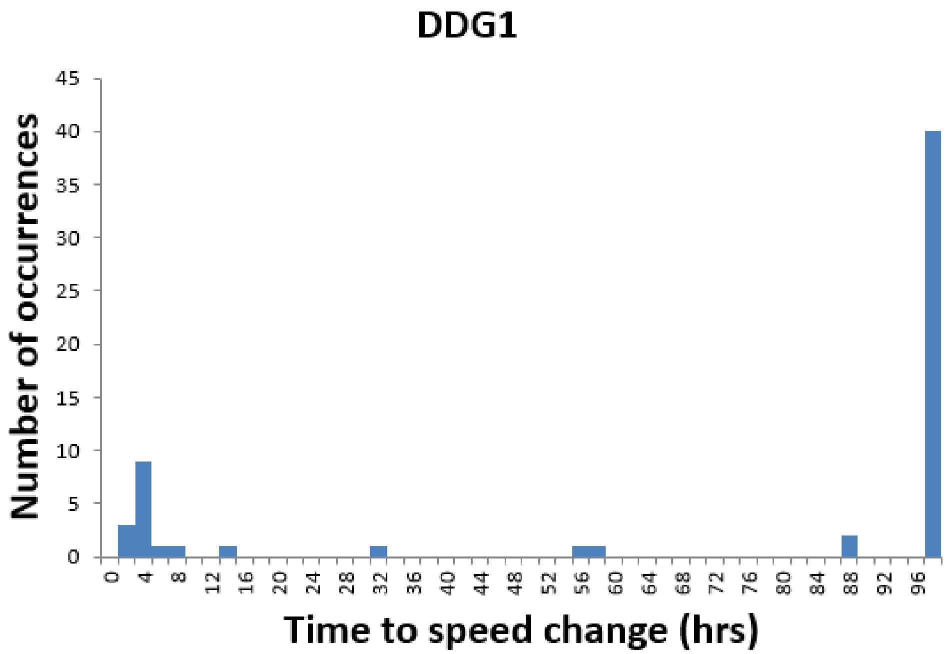


Figure 42. DDG2A TTSC

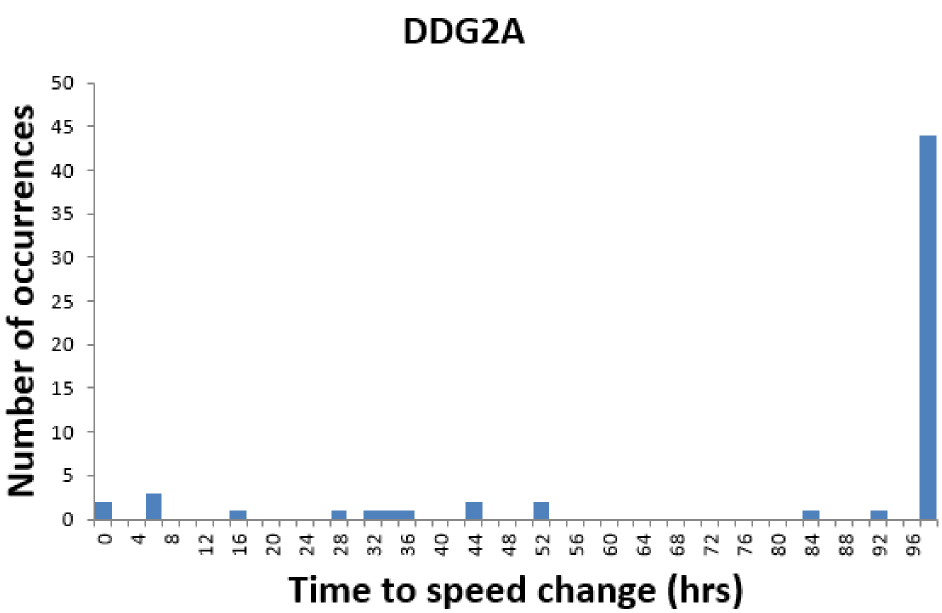


Figure 43. FFG7 TTSC

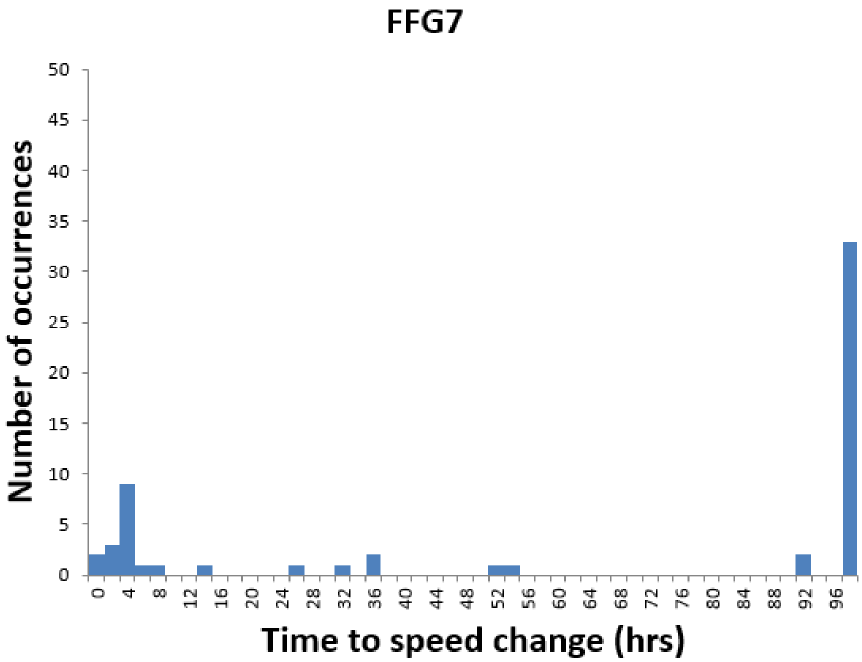


Figure 44. LCS1 TTSC

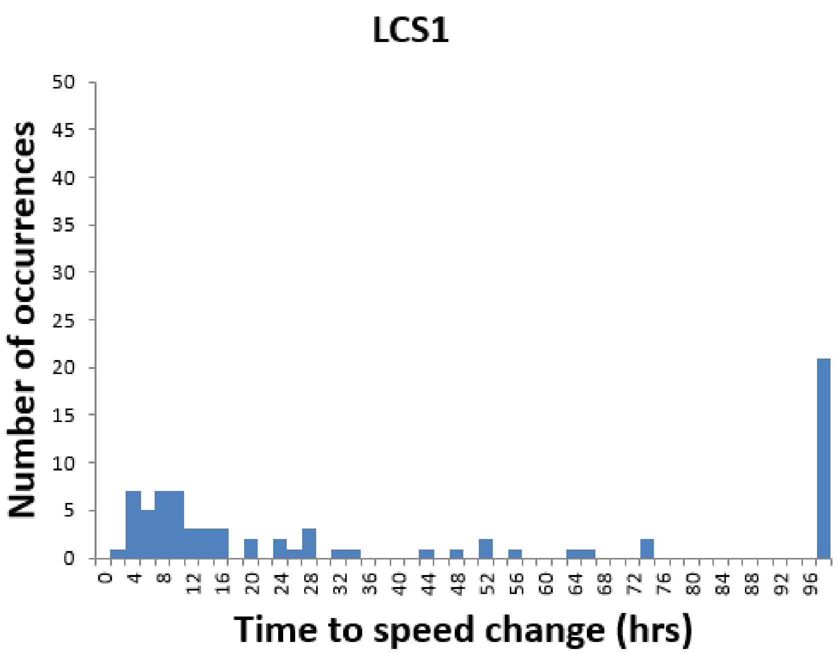


Figure 45. LCS2 TTSC

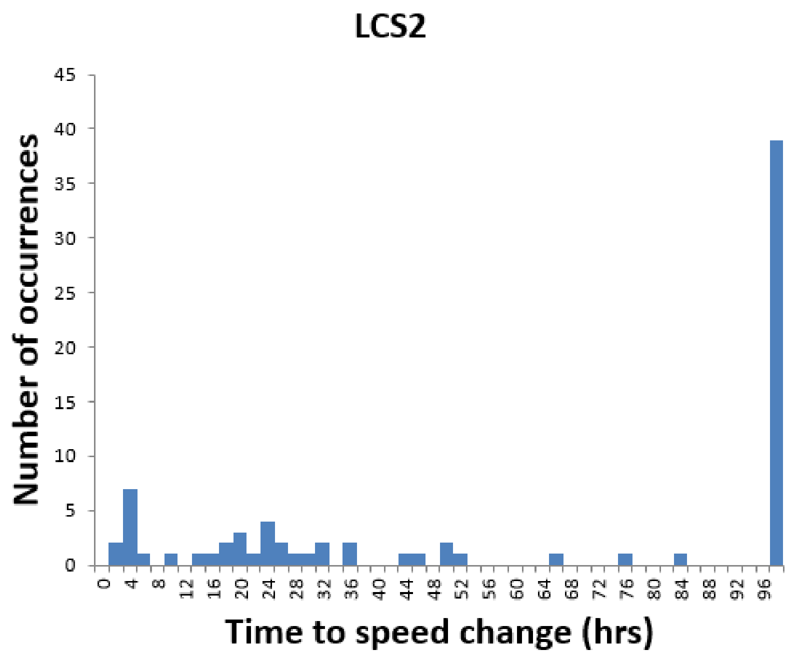


Figure 46. LHA1 TTSC

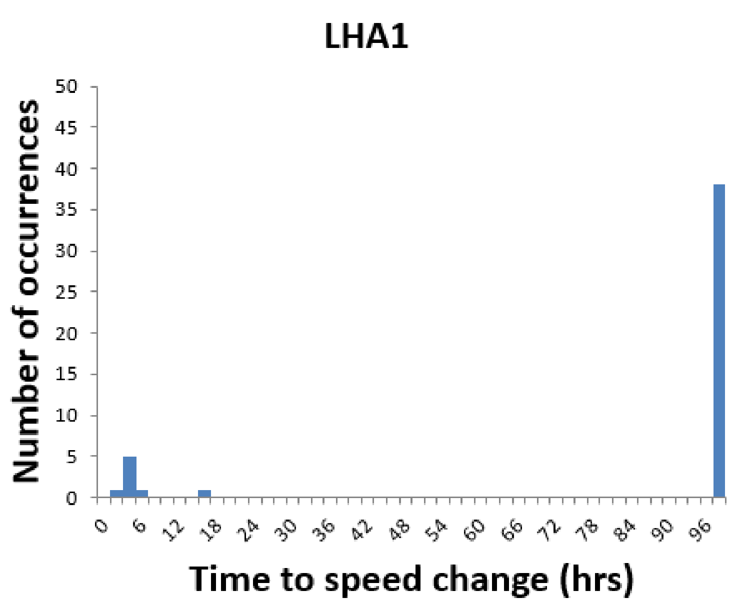


Figure 47. LHD1 TTSC

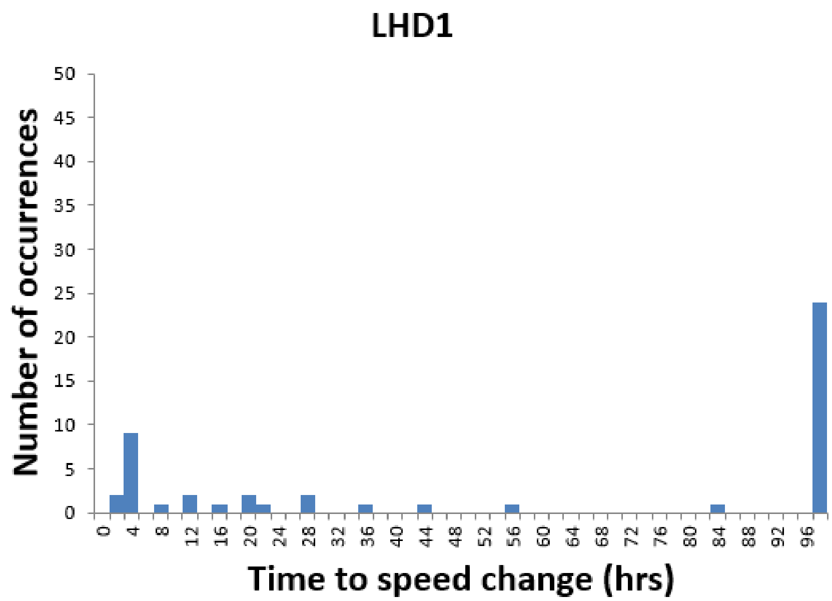


Figure 48. LPD4 TTSC

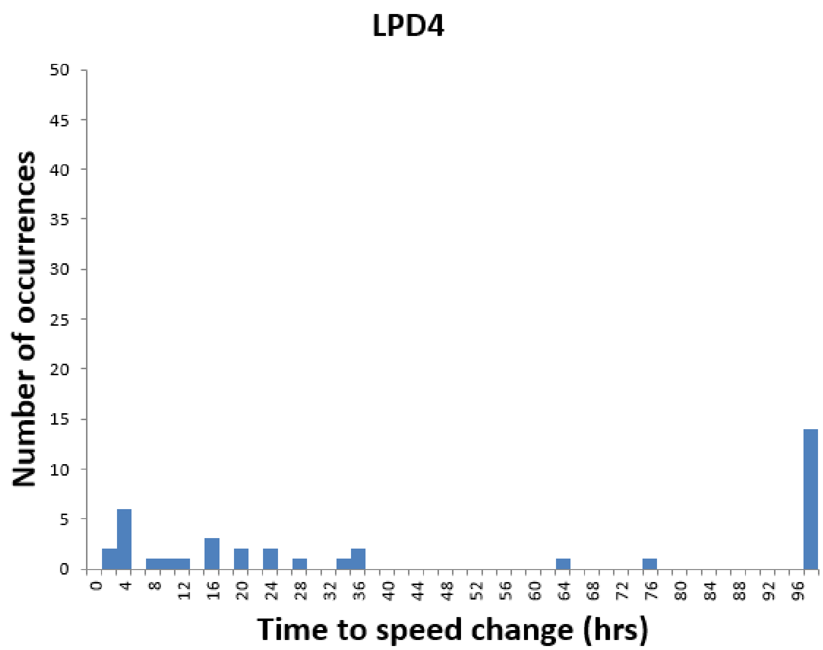


Figure 49.   LSD41 TTSC

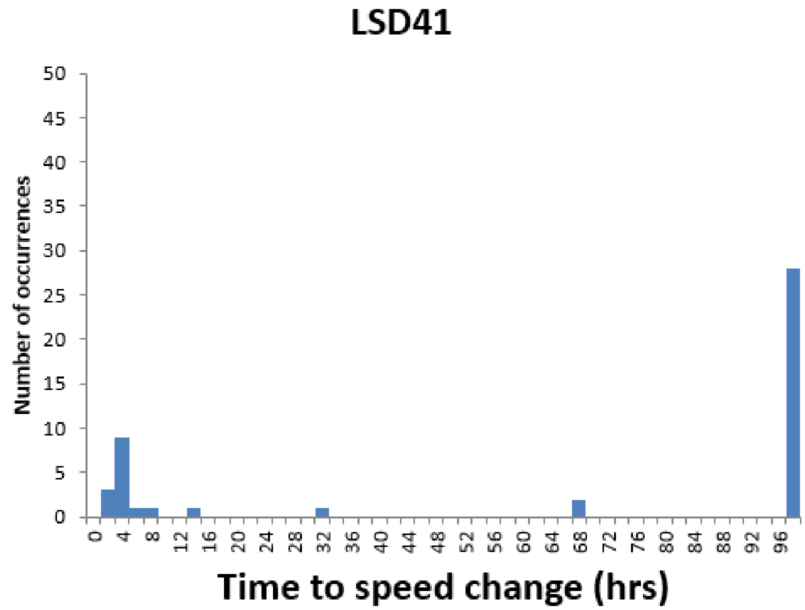
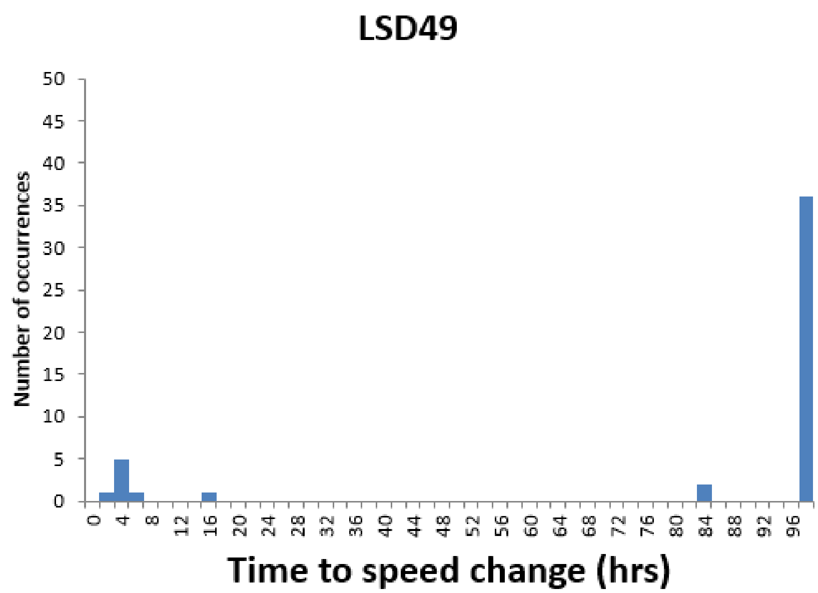


Figure 50.   LSD49 TTSC



APPENDIX D. DYNAMIC OTTER VBA CODE

```
‘groups try to stay at front of window, so instead of spread constraint, have groups constrained such that
‘every speed change must last at least an hour and groups try to be at front of window for drills
‘any speed change must last at least an hour. large changes cause engine config change, small changes
insignificant
‘assuming drill times of < 4 hours and no drills with negative forward progress, spread will be at most 4
hours.
‘assume that in all other cases groups will be moving as a single (combined) unit

Public startTime As Date ‘time and date at start of model
Public intervalSize As Integer ‘time interval size in minutes
Public intervalCount As Integer ‘total number of intervals
Public currentInterval As Integer ‘current time interval in the schedule
Public currentSpeeds() As Integer
Public targetDistance As Double
Public PIMDistance As Double
Public averageSpeed As Double
Public oceanSpeed As Double
Public Const maxSpeed = 40
Public minSpeedDuration As Integer ‘minimum number of time intervals between speed changes
Public Const scheduleStartRow = 6 ‘first row of schedule for speeds, with ship header row as row 1
Public Const headerStartRow = 10
Public bShips() As battleShip ‘holds the battleships
Public shipNames() As String ‘holds the name of each ship type
Public maxSpread As Double ‘maximum spread between two ships at any time
Public maxSpreadAllowed As Integer ‘max spread allowed by user
Public countDrillsInSpread As Boolean
Public Type battleShip
‘count As Integer ‘number of type of ship
shipType As String ‘Type of ship
distance As Double ‘distance traveled thus far
finalOffset As Double ‘final offset from PIM window center at end of travel
initialOffset As Double ‘initial offset from PIM window center at start of travel
drillStarts(2) As Integer ‘time intervals when this ship starts a drill
drillDurations(2) As Integer ‘duration of drills in time intervals
drillSpeeds(2) As Integer ‘speed during drill
drillFP(2) As Double ‘forward progress made by each drill per time interval
speedIntervals(maxSpeed) As Integer ‘array containing how many time intervals to spend at each speed
(index)
fuelBurned As Double ‘fuel burned under given schedule
fuelBurnedOld As Double ‘fuel burned under old practices, extrapolated from daily average
‘engineConfig(maxSpeed) As String ‘array of engine configurations with speed as index
offset As Double ‘distance from center of PIM window
highSpeed As Integer ‘fastest travel speed
lowSpeed As Integer ‘slowest travel speed
biggestLeap As Double ‘biggest possible speed change multiplied by interval. Used to determine
impossible spread
lastSpeedChangeTime As Integer ‘time interval where last speed change took place
lastModeChangeTime As Integer ‘time interval where last mode change took place
lastSpeed As Integer ‘speed at which ship was traveling during last interval
index As Integer ‘position in bShips array
```

```
minSpeedTime As Integer ‘minimum number of intervals required before changing speeds (same engine config)
minModeTime As Integer ‘minimum number of intervals required before changing engine configs
RushSpeed As Integer ‘speed at which to rush to front of PIM window
rushing As Boolean ‘whether or not ship is rushing to catch up
countInSpread As Boolean ‘determines whether or not to include ship in spread.
needNewSpeeds As Boolean
‘targetDist As Double ‘target distance to be at at a a certain time
‘targetTime As Integer ‘time interval pertaining to targetDist

End Type


Sub buildSchedule()
‘master subroutine that calls all subs/functions needed to build and present the schedule

countDrillsInSpread = False
currentInterval = 0
With ThisWorkbook.Sheets(“Short Term Planner”)
‘set startTime, intervalSize, and currentInterval
startTime = .Range(“PlannerStartTime”).Value
targetDistance = .Range(“PlannerDistance”).Value
intervalSize = .Range(“PlannerTimeInterval”).Value
intervalCount = .Range(“PlannerDuration”).Value * 60 / intervalSize
‘change this to accomodate different ship limits
minSpeedDuration = 60 / intervalSize
‘reset PIM and average Speed
PIMDistance = 0
averageSpeed = .Range(“PlannerAverageSpeedLand”).Value
oceanSpeed = .Range(“PlannerOceanCurrent”).Value
maxSpreadAllowed = .Range(“PlannerMaxSpread”).Value

End With

maxSpread = 0
‘create ships and populate arrays
Call buildArrays
‘clear old schedule and update the headers on the Schedule sheet
Call clearSchedule
Call updateHeaders
‘label timeline
Call labelTimeline
‘plan ship schedules
Call planShipSchedules
Call getOldBurnRate
Call recordFuelSaved
ThisWorkbook.Sheets(“Short Term Schedule”).Select
Application.Calculation = xlCalculationAutomatic

End Sub

Sub planShipSchedules()
‘for each ship, iterates through each time interval to place speeds and drills
Dim ship As battleShip
For currentInterval = 0 To intervalCount - 1
```

```
‘check spread status
For j = 0 To UBound(bShips)
ship = bShips(j)
Call checkSpreadAfterDrills(ship)
Next j
‘get this interval’s speeds
For j = 0 To UBound(bShips)
ship = bShips(j)
If currentInterval < ship.drillStarts(1) Then
‘before drill 1
currentSpeeds(j) = getIntervalSpeed(ship, False)
ElseIf currentInterval >= ship.drillStarts(1) And currentInterval < ship.drillStarts(1) +
ship.drillDurations(1) Then
‘drill 1
ElseIf currentInterval < ship.drillStarts(2) Then
‘after drill 1, before drill 2
currentSpeeds(j) = getIntervalSpeed(ship, False)
ElseIf currentInterval >= ship.drillStarts(2) And currentInterval < ship.drillStarts(2) +
ship.drillDurations(2) Then
‘drill 2
Else
‘after drill 2
currentSpeeds(j) = getIntervalSpeed(ship, False)
End If
Next j
‘record this interval’s speeds
For j = 0 To UBound(bShips)
ship = bShips(j)
If currentInterval < ship.drillStarts(1) Then
‘before drill 1
Call recordSpeed(ship, currentSpeeds(j))
ElseIf currentInterval >= ship.drillStarts(1) And currentInterval < ship.drillStarts(1) +
ship.drillDurations(1) Then
‘drill 1
Call recordDrill(ship, currentInterval)
ElseIf currentInterval < ship.drillStarts(2) Then
‘after drill 1, before drill 2
Call recordSpeed(ship, currentSpeeds(j))
ElseIf currentInterval >= ship.drillStarts(2) And currentInterval < ship.drillStarts(2) +
ship.drillDurations(2) Then
‘drill 2
Call recordDrill(ship, currentInterval)
Else
‘after drill 2
Call recordSpeed(ship, currentSpeeds(j))
End If
Next j
If findSpread() > maxSpread Then
maxSpread = findSpread()
End If
If findSpread() > maxSpreadAllowed Then
With ThisWorkbook.Sheets(“Short Term Schedule”)
For i = (1) To 44 Step 3

‘go to correct row
```

```
row = scheduleStartRow + currentInterval
'record speed and current distance
.Range("ShipHeaders").Cells(row, i).Interior.ColorIndex = 54
.Range("ShipHeaders").Cells(row, i + 1).Interior.ColorIndex = 54
.Range("ShipHeaders").Cells(row, i + 2).Interior.ColorIndex = 54
Next i
End With
End If
Next currentInterval
If maxSpread > maxSpreadAllowed Then
MsgBox ("Broke Spread")
End If
ThisWorkbook.Sheets("Short Term Schedule").Range("ScheduleLargestSpread").Cells(1, 1).Value =
maxSpread
End Sub
Sub getOldBurnRate()
'get old fuel burn for comparison
'uses same daily burn calculation as TFP
Dim ship As battleShip
Dim fuel As Double
Dim days As Double
Dim drillHoursPerDay As Integer
Dim avgSpeed As Double 'average speed after acounting for PIM position
days = intervalCount * (intervalSize / 60) / 24
For j = 0 To UBound(bShips)
ship = bShips(j)
With ThisWorkbook.Sheets("Short Term Schedule")
Call getOldFuelWithPIM(ship)
.Range("ShipHeaders").Cells(2, 3 * j + 1).Value = "Fuel Burned: " &
Application.WorksheetFunction.Round(bShips(j).fuelBurned, 1) & " gallons"
.Range("ShipHeaders").Cells(3, 3 * j + 1).Value = "Fuel saved: " &
Application.WorksheetFunction.Round(bShips(j).fuelBurnedOld - bShips(j).fuelBurned, 1) & " gallons"
.Range("ShipHeaders").Cells(4, 3 * j + 1).Value = "Extra ToS: " &
Application.WorksheetFunction.Round((bShips(j).fuelBurnedOld - bShips(j).fuelBurned) /
Sheets(bShips(j).shipType).Range(LCase(bShips(j).shipType) & "ToSRate").Cells(1, 1).Value, 1) & "
hours"
End With
With ThisWorkbook.Sheets("Comparison Schedule")
.Range("ShipHeaders").Cells(2, 3 * j + 1).Value = "Fuel Burned: " &
Application.WorksheetFunction.Round(bShips(j).fuelBurnedOld, 1) & " gallons"
End With
Next j
End Sub

Sub updateHeaders()
'update the headers/boxes on the schedule page to reflect the ship names and transit parameters
With ThisWorkbook.Sheets("Short Term Schedule")
'clear previous ship headers
.Range("ShipHeaders").Value = ""
'write in new ship headers
i = 1
For s = 0 To UBound(bShips)
.Range("ShipHeaders").Cells(1, i).Value = "Ship " & s + 1 & ": " & bShips(s).shipType 'ship names
.Range("ShipHeaders").Cells(5, i).Value = "Spd (kts)" 'ship names
.Range("ShipHeaders").Cells(5, i + 1).Value = "Dist (nm)" 'distance
```

```
.Range("ShipHeaders").Cells(5, i + 2).Value = "Mode" 'engine config
i = i + 3
Next s
'populate transit summary boxes
.Range("ScheduleDistance").Value = ThisWorkbook.Sheets("Short Term
Planner").Range("PlannerDistance").Value
.Range("ScheduleDuration").Value = ThisWorkbook.Sheets("Short Term
Planner").Range("PlannerDuration").Value
.Range("ScheduleOceanCurrent").Value = ThisWorkbook.Sheets("Short Term
Planner").Range("PlannerOceanCurrent").Value
.Range("ScheduleTimeInterval").Value = ThisWorkbook.Sheets("Short Term
Planner").Range("PlannerTimeInterval").Value
.Range("ScheduleStartTime").Value = ThisWorkbook.Sheets("Short Term
Planner").Range("PlannerStartTime").Value
End With

With ThisWorkbook.Sheets("Comparison Schedule")
'clear previous ship headers
.Range("ShipHeaders").Value = ""
'write in new ship headers
i = 1
For s = 0 To UBound(bShips)
.Range("ShipHeaders").Cells(1, i).Value = "Ship " & s + 1 & ": " & bShips(s).shipType 'ship names
.Range("ShipHeaders").Cells(4, i).Value = "Spd (kts)" 'ship names
.Range("ShipHeaders").Cells(4, i + 1).Value = "Dist (nm)" 'distance
.Range("ShipHeaders").Cells(4, i + 2).Value = "Mode" 'engine config
i = i + 3
Next s
'populate transit summary boxes
.Range("ScheduleDistance").Value = ThisWorkbook.Sheets("Short Term
Planner").Range("PlannerDistance").Value
.Range("ScheduleDuration").Value = ThisWorkbook.Sheets("Short Term
Planner").Range("PlannerDuration").Value
.Range("ScheduleOceanCurrent").Value = ThisWorkbook.Sheets("Short Term
Planner").Range("PlannerOceanCurrent").Value
.Range("ScheduleTimeInterval").Value = ThisWorkbook.Sheets("Short Term
Planner").Range("PlannerTimeInterval").Value
.Range("ScheduleStartTime").Value = ThisWorkbook.Sheets("Short Term
Planner").Range("PlannerStartTime").Value
End With
End Sub

Sub clearSchedule()
'clears the schedule page

With ThisWorkbook.Sheets("Short Term Schedule")
.Rows(scheduleStartRow + headerStartRow - 1 & ":" & .Rows.count).Delete
End With
With ThisWorkbook.Sheets("Comparison Schedule")
.Rows(scheduleStartRow + headerStartRow - 1 & ":" & .Rows.count).Delete
End With
End Sub

Sub labelTimeline()
'creates timeline on schedule sheet based on intervals
```

```
i = 2
Dim dist As Double
Dim time As Date
With ThisWorkbook.Sheets("Short Term Schedule")
time = .Range("ScheduleStartTime").Value
dist = 0
While (i - 2) * intervalSize / 60 < .Range("ScheduleDuration").Value
.Range("TimeHeader").Cells(i, 1).Value = DateAdd("n," (i - 2) * intervalSize, time)
.Range("TimeHeader").Cells(i, 2).Value = dist
i = i + 1
dist = dist + (averageSpeed * (intervalSize / 60))
Wend
End With
i = 2
With ThisWorkbook.Sheets("Comparison Schedule")
time = .Range("ScheduleStartTime").Value
dist = 0
While (i - 2) * intervalSize / 60 < .Range("ScheduleDuration").Value
.Range("TimeHeader").Cells(i, 1).Value = DateAdd("n," (i - 2) * intervalSize, time)
.Range("TimeHeader").Cells(i, 2).Value = dist
i = i + 1
dist = dist + (averageSpeed * (intervalSize / 60))
Wend
End With
End Sub


Sub buildArrays()
'populate the array of bShips and shipNames
'clear previous values from arrays and set to size 0
ReDim shipNames(0)
ReDim bShips(0)
ReDim currentSpeeds(0)
Dim tempSpeedArray(40) As Integer

With ThisWorkbook.Sheets("Short Term Planner")
'count ship types used in this model
Dim i As Integer
i = -1
For Each s In .Range("PlannerShipType").Cells
If s.Text <> "none" Then
i = i + 1
End If
Next s
'safety in case no bShips
If i < 0 Then
Exit Sub
End If
'resize ship arrays
ReDim shipNames(i) As String
ReDim bShips(i) As battleShip
ReDim currentSpeeds(i)
'populate ship arrays
i = 0
For s = 1 To .Range("PlannerShipType").Cells.count
```

```
If .Range(“PlannerShipType”).Cells(s, 1).Text <> “none” Then
‘add to shipNames
shipNames(i) = .Range(“PlannerShipType”).Cells(s, 1).Text
‘create new battleship
Dim bShip As battleShip
bShip.shipType = shipNames(i)
bShip.distance = .Range(“PlannerStartingOffset”).Cells(s, 1).Value
bShip.initialOffset = .Range(“PlannerStartingOffset”).Cells(s, 1).Value
bShip.finalOffset = .Range(“PlannerFinalOffset”).Cells(s, 1).Value
bShip.drillStarts(1) = getInterval(CDate(.Range(“Drill1StartTime”).Cells(s, 1).Value))
If bShip.drillStarts(1) > 0 Then
bShip.drillDurations(1) = Round(.Range(“Drill1Duration”).Cells(s, 1).Value * 60 / intervalSize, 0)
bShip.drillSpeeds(1) = .Range(“Drill1Speed”).Cells(s, 1).Value
bShip.drillFP(1) = .Range(“Drill1ForwardProgress”).Cells(s, 1).Value / bShip.drillDurations(1) +
(oceanSpeed * intervalSize / 60)
Else
bShip.drillDurations(1) = 0
bShip.drillSpeeds(1) = 0
bShip.drillFP(1) = 0
End If
bShip.drillStarts(2) = getInterval(CDate(.Range(“Drill2StartTime”).Cells(s, 1).Value))
If bShip.drillStarts(2) > 0 Then
bShip.drillDurations(2) = Round(.Range(“Drill2Duration”).Cells(s, 1).Value * 60 / intervalSize, 0)
bShip.drillSpeeds(2) = .Range(“Drill2Speed”).Cells(s, 1).Value
bShip.drillFP(2) = .Range(“Drill2ForwardProgress”).Cells(s, 1).Value / bShip.drillDurations(2) +
(oceanSpeed * intervalSize / 60)
Else
bShip.drillDurations(2) = 0
bShip.drillSpeeds(2) = 0
bShip.drillFP(2) = 0
End If
bShip.countInSpread = True
bShip.needNewSpeeds = False
bShip.lastSpeed = 0
bShip.rushing = False
bShip.fuelBurned = 0
bShip.fuelBurnedOld = 0
‘get slowest, fastest speeds, and biggest leap
bShip.lowSpeed = getSlowestSpeed(bShip)
bShip.highSpeed = getFastestSpeed(bShip)
bShip.RushSpeed = ThisWorkbook.Sheets(UCase(bShip.shipType)).Range(LCase(bShip.shipType) &
“RushSpeed”).Cells(1, 1).Value
‘get # intervals spent at each speed
Call getSpeedIntervalsArray(bShip, bShip.speedIntervals)
‘min speed and mode times
bShip.minModeTime =
Application.WorksheetFunction.RoundUp(ThisWorkbook.Sheets(UCase(bShip.shipType)).Range(LCase(b
Ship.shipType) & “ModeMinTime”).Cells(1, 1).Value / intervalSize, 0)
bShip.minSpeedTime =
Application.WorksheetFunction.RoundUp(ThisWorkbook.Sheets(UCase(bShip.shipType)).Range(LCase(b
Ship.shipType) & “SpeedMinTime”).Cells(1, 1).Value / intervalSize, 0)
‘initialize last change times
bShip.lastSpeedChangeTime = -bShip.minSpeedTime ‘set to -minSpeedtime so speed can change at time
interval 0
```

```
bShip.lastModeChangeTime = -bShip.minModeTime ‘set to -minModetime so speed can change at time
interval 0
‘record bship index
bShip.index = i
‘add bShip to the bShips array
bShips(i) = bShip
i = i + 1
End If
Next s
End With
End Sub

Function getInterval(time As Date) As Integer
‘updated for V2
‘compares a given time to the transit start time and interval size to return the corresponding time interval
‘define startTime, intervalSize if there isn’t one defined
With ThisWorkbook.Sheets(“Short Term Planner”)
startTime = .Range(“PlannerStartTime”).Value
intervalSize = .Range(“PlannerTimeInterval”).Value
End With
If startTime > time Then
getInterval = -1
Else
‘get time difference in minutes
Dim minutesDiff As Integer
minutesDiff = DateDiff(“n,” startTime, time)
‘convert to inteval #, 0 indexed
getInterval = Round(minutesDiff / intervalSize, 0)
End If

End Function

Function getSlowestSpeed(s As battleShip) As Integer
‘returns the slowest speed remaining for a ship

For i = 0 To maxSpeed
If s.speedIntervals(i) > 0 Then
s.lowSpeed = i
getSlowestSpeed = i
Exit For
End If
Next i
End Function

Function getFastestSpeed(s As battleShip) As Integer
‘returns the fastest speed remaining for a ship
For i = maxSpeed To 0 Step -1
If s.speedIntervals(i) > 0 Then
s.highSpeed = i
getFastestSpeed = i
Exit For
End If
Next i
End Function
```

```
Function findSpread() As Double
'returns the current spread of the group in nm
findSpread = bShips(findHead).distance - bShips(findTail).distance - (bShips(findHead).lastSpeed -
bShips(findTail).lastSpeed) * intervalSize / 60
End Function

Function findHead() As Integer
'returns the bShips index of ship at front of pack

Dim maxDist As Double
maxDist = -9999
For s = 0 To UBound(bShips)
If maxDist < bShips(s).distance And bShips(s).countInSpread = True Then
maxDist = bShips(s).distance
findHead = s
End If
Next s
End Function

Function findTail() As Integer
'returns the bShips index of ship at back of pack

Dim minDist As Double
minDist = 9999
For s = 0 To UBound(bShips)
If minDist > bShips(s).distance And bShips(s).countInSpread = True Then
minDist = bShips(s).distance
findTail = s
End If
Next s
End Function

Function getPIMLeadAtTime(t As Integer) As Double
'returns the PIM leading edgedistance at given time interval
getPIMLeadAtTime = (4 + (t * intervalSize / 60)) * averageSpeed
End Function

Function getIntervalSpeed(ship As battleShip, bypass As Boolean) As Integer
'returns the speed at which the ship will travel for this interval
getIntervalSpeed = ship.lastSpeed 'hold current speed as default
Dim PIMGain As Double 'distance gained on PIM window by traveling at a speed
Dim dur As Integer 'min time intervals required to hold a speed
Dim speed As Integer
'only possibly change speeds if have been at current speed for long enough or no more time at last speed
'If currentInterval - ship.lastSpeedChangeTime >= minSpeedDuration Or
ship.speedIntervals(ship.lastSpeed) = 0 Then
If ship.needNewSpeeds = True Then
Call getSpeedIntervalsArray(ship, ship.speedIntervals)
Call getSpeedIntervalsArray(bShips(ship.index), bShips(ship.index).speedIntervals)
End If
If currentInterval - ship.lastSpeedChangeTime >= ship.minSpeedTime Or
ship.speedIntervals(ship.lastSpeed) = 0 Then
'iterate through possible speeds, highest speed 1st
For speed = maxSpeed To 0 Step -1
'only consider speeds that the ship will use
```

```
If ship.speedIntervals(speed) > 0 Then
‘only consider speeds in same mode unless minModeTime has passed since last mode change
If StrComp(modeAtSpeed(ship, speed), modeAtSpeed(ship, ship.lastSpeed)) = 0 Or currentInterval -
ship.lastModeChangeTime >= ship.minModeTime Or bypass = True Then
‘adjust min required duration
If speed = ship.lastSpeed Then ‘can hold current speed for an interval ok
dur = 1
ElseIf ship.speedIntervals(speed) < ship.minSpeedTime Then ‘Or ship.speedIntervals(speed) <
ship.minModeTime Then ‘if speed has fewer than minSpeedDuration intervals remaining
dur = ship.speedIntervals(speed)
Else
If StrComp(modeAtSpeed(ship, speed), modeAtSpeed(ship, ship.lastSpeed)) = 0 Then
dur = ship.minSpeedTime
Else
dur = ship.minModeTime
End If

End If
x = ship.index
‘choose speed if it won’t break PIM if held for min duration
gain = (speed + oceanSpeed) * intervalSize * dur / 60 ‘min possible gain on PIM
If ship.distance + gain <= getPIMLeadAtTime(currentInterval + dur) And checkSpread(ship, speed, dur) =
True Then
‘ship can travel at this speed for the min required duration
getIntervalSpeed = speed
‘prioritize high speeds

‘if set to rush after drills, and ship is recovering after drills
If Sheets(“Short Term Planner”).RushAfterDrillsButton.Value = True And ship.countInSpread = False
Then
If ship.rushing = True Then
‘rush behavior overrides speed
getIntervalSpeed = ship.RushSpeed
End If
End If
Exit For
Else
x = 3
End If
End If
End If

If speed = 0 And bypass = False Then
q = ship.shipType
q2 = currentInterval
getIntervalSpeed = getIntervalSpeed(ship, True)
End If
Next speed
End If
End Function

Sub recordSpeed(ship As battleShip, speed As Integer)
‘records the given speed for the given ship type into the schedule.
‘Also updates ship’s speed array and distance for the ship
‘ship.distance = ship.distance + speed * intervalSize / 60
```

```
bShips(ship.index).speedIntervals(speed) = ship.speedIntervals(speed) - 1
‘find right column in header array
With ThisWorkbook.Sheets(“Short Term Schedule”)
i = 1 + 3 * ship.index
‘go to correct row
row = scheduleStartRow + currentInterval
‘record speed and current resulting distance
.Range(“ShipHeaders”).Cells(row, i).Value = speed
.Range(“ShipHeaders”).Cells(row, i + 1).Value = ship.distance
.Range(“ShipHeaders”).Cells(row, i + 2).Value =
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & “ModeUsed”).Cells(speed +
1, 1).Value
‘update speed change time if speed changed
If speed <> ship.lastSpeed Then
.Range(“ShipHeaders”).Cells(row, i).Interior.ColorIndex = 27
.Range(“ShipHeaders”).Cells(row, i + 1).Interior.ColorIndex = 27
.Range(“ShipHeaders”).Cells(row, i + 2).Interior.ColorIndex = 27
If modeAtSpeed(ship, speed) <> modeAtSpeed(ship, ship.lastSpeed) Then
bShips(ship.index).lastModeChangeTime = currentInterval
.Range(“ShipHeaders”).Cells(row, i).Interior.ColorIndex = 45
.Range(“ShipHeaders”).Cells(row, i + 1).Interior.ColorIndex = 45
.Range(“ShipHeaders”).Cells(row, i + 2).Interior.ColorIndex = 45
End If
bShips(ship.index).lastSpeedChangeTime = currentInterval
bShips(ship.index).lastSpeed = speed
ElseIf ship.countInSpread = False Then
.Range(“ShipHeaders”).Cells(row, i).Interior.ColorIndex = 43
.Range(“ShipHeaders”).Cells(row, i + 1).Interior.ColorIndex = 43
.Range(“ShipHeaders”).Cells(row, i + 2).Interior.ColorIndex = 43
End If
bShips(ship.index).fuelBurned = bShips(ship.index).fuelBurned + CDbl(intervalSize / 60) *
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) &
“BurnRateUsed”).Cells(speed + 1, 1).Value ‘burn fuel during transit
End With
bShips(ship.index).distance = bShips(ship.index).distance + CDbl((speed + oceanSpeed) * intervalSize /
60)
End Sub

Sub recordDrill(ByRef ship As battleShip, time As Integer)
‘records the drills for the given ship into the schedule

‘determin which drill
Dim drillNum As Integer
If time < ship.drillStarts(2) Or ship.drillStarts(2) < 0 Then
drillNum = 1
Else: drillNum = 2
End If

bShips(ship.index).countInSpread = False

With ThisWorkbook.Sheets(“Short Term Schedule”)
i = 1 + 3 * ship.index
‘go to correct row
row = scheduleStartRow + currentInterval
‘record speed and current distance
```

```
.Range("ShipHeaders").Cells(row, i).Value = "Drill " & drillNum & "; " & ship.drillSpeeds(drillNum)
.Range("ShipHeaders").Cells(row, i).Interior.ColorIndex = 20
.Range("ShipHeaders").Cells(row, i + 1).Value = ship.distance
.Range("ShipHeaders").Cells(row, i + 1).Interior.ColorIndex = 20
.Range("ShipHeaders").Cells(row, i + 2).Value =
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) &
"ModeUsed").Cells(ship.drillSpeeds(drillNum), 1).Value
.Range("ShipHeaders").Cells(row, i + 2).Interior.ColorIndex = 20
'update distance
bShips(ship.index).distance = bShips(ship.index).distance + ship.drillFP(drillNum)
bShips(ship.index).fuelBurned = bShips(ship.index).fuelBurned + CDbl(intervalSize / 60) *
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) &
"BurnRateUsed").Cells(ship.drillSpeeds(drillNum) + 1, 1).Value 'burn fuel during drill
End With

End Sub

Sub getSpeedIntervalsArray(ByRef ship As battleShip, ByRef intervals() As Integer)
'populates the ships speedintervals array.
'still needs to be tested.
'ReDim intervals(40)
'get required distance and time
Dim drillDist As Double
Dim drillTime As Integer
Dim dist As Double
Dim duration As Integer

ship.needNewSpeeds = False

drillDist = 0
drillTime = 0

If currentInterval <= ship.drillStarts(1) Then
drillDist = drillDist + ship.drillDurations(1) * ship.drillFP(1) + (oceanSpeed * (ship.drillDurations(1)) *
(intervalSize / 60))
drillTime = drillTime + ship.drillDurations(1)
End If

If currentInterval <= ship.drillStarts(2) Then
drillDist = drillDist + ship.drillDurations(2) * ship.drillFP(2) + (oceanSpeed * ship.drillDurations(2) *
(intervalSize / 60))
drillTime = drillTime + ship.drillDurations(2)
End If
'distance of transit - drill dist - starting position - (ocean speed * (time-drill time))
dist = targetDistance + ship.finalOffset - ship.distance - oceanSpeed * (intervalCount - currentInterval -
drillTime) * (intervalSize / 60) - drillDist '+ (ship.lastSpeed * (intervalSize / 60))
duration = intervalCount - currentInterval - drillTime
'run the solver for this ship
Call solveShip(ship.shipType, dist, duration, intervalSize)
'populate speedIntervals, adjust for non-integers in solver
Dim temp As Double
Dim foundLow As Boolean
foundHigh = False
For i = 40 To 0 Step -1
temp = ThisWorkbook.Sheets("Solver").Range("SolverIntervalRange").Cells(i + 1, 1).Value
```

```
If temp > 0.01 And foundHigh = False Then
If temp - Application.WorksheetFunction.RoundDown(temp, 0) > 0.05 Then
intervals(i) = Application.WorksheetFunction.RoundUp(temp, 0)
Else
intervals(i) = Application.WorksheetFunction.RoundDown(temp, 0)
End If
foundHigh = True
Else
If temp - Application.WorksheetFunction.RoundDown(temp, 0) > 0.95 Then
intervals(i) = Application.WorksheetFunction.RoundUp(temp, 0)
Else
intervals(i) = Application.WorksheetFunction.RoundDown(temp, 0)
End If

End If
Next i
End Sub
Function modeAtSpeed(ship As battleShip, speed As Integer) As String
‘returns the mode for a given ship and speed
modeAtSpeed = ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) &
“ModeUsed”).Cells(speed + 1, 1).Value
End Function


Sub getOldFuelWithPIM(ByRef ship As battleShip)
‘gets the total fuel used by given ship under old practices. Assumes ships will rush to
‘front of pim window, and hold pim speed while at front. Each ship has its own rush speed

‘check that rush speed set for ship can complete transit on time
‘get distance to be traveled by non-drill transit
distcheck = (averageSpeed * intervalCount * intervalSize / 60) - ship.drillFP(1) * ship.drillDurations(1) -
ship.drillFP(2) * ship.drillDurations(2) + ship.finalOffset - ThisWorkbook.Sheets(“Short Term
Planner”).Range(“PlannerStartingOffset”).Cells(ship.index + 1, 1).Value
intervalCountTran = intervalCount - ship.drillDurations(1) - ship.drillDurations(2) ‘get # intervals spent
transiting, not including drills

If (ship.RushSpeed + oceanSpeed) * intervalCountTran * intervalSize / 60 < distcheck Then
‘rush speed too low, reset to highest possible speed
MsgBox (“Ship “ & ship.index & “ of type “ & ship.shipType & “ rush speed is too low to complete transit
on time.” & vbNewLine & “Fuel comparison calculator will use a rush speed of “ & getMaxSpeed(ship) &
“kts instead of the user-specified “ & ship.RushSpeed & “kts.” & vbNewLine & “This has no impact on the
generated schedule and will only affect the predicted fuel saved by using OTTER.”)
bShips(ship.index).RushSpeed = getMaxSpeed(ship)
ship.RushSpeed = getMaxSpeed(ship)
If (ship.RushSpeed + oceanSpeed) * intervalCountTran * intervalSize / 60 < distcheck Then
‘even max speed is too slow
MsgBox (“Even the new rush speed is too slow. Brandon should build some checks into the start of the
scheduling process to make sure that this can’t happen”)
End If
End If

Dim time As Date
Dim speed As Integer
Dim dist As Double
Dim pimDist As Double
```

```
Dim burn As Double

time = startTime
dist = ThisWorkbook.Sheets("Short Term Planner").Range("PlannerStartingOffset").Cells(ship.index + 1,
1).Value
pimDist = 0
'With ThisWorkbook.Sheets("ScheduleTesting")
With ThisWorkbook.Sheets("Comparison Schedule")
'record ship in test schedule
For i = 0 To intervalCount - 1

j = 1 + 3 * ship.index

'go to correct row
row = scheduleStartRow + i - 1

'until 1st drill
If i < ship.drillStarts(1) Then
'rush to front of window
If dist + ((ship.RushSpeed + oceanSpeed) * intervalSize / 60) <= pimDist + 4 * averageSpeed Then
speed = ship.RushSpeed
'hold pim speed
Else
speed = Application.WorksheetFunction.RoundDown(averageSpeed, 0) - oceanSpeed
End If
'record speed and current resulting distance
.Range("ShipHeaders").Cells(row, j).Value = speed
.Range("ShipHeaders").Cells(row, j + 1).Value = dist
.Range("ShipHeaders").Cells(row, j + 2).Value =
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & "ModeUsed").Cells(speed +
1, 1).Value

burn = burn + CDbl(intervalSize / 60) *
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) &
"BurnRateUsed").Cells(speed + 1, 1).Value 'burn fuel during transit
dist = dist + (speed + oceanSpeed) * intervalSize / 60
pimDist = pimDist + averageSpeed * intervalSize / 60
time = DateAdd("n," intervalSize, time)


'do drill 1
ElseIf i >= ship.drillStarts(1) And i < ship.drillStarts(1) + ship.drillDurations(1) Then
speed = ship.drillSpeeds(1)
.Range("ShipHeaders").Cells(row, j).Value = speed
.Range("ShipHeaders").Cells(row, j + 1).Value = dist
.Range("ShipHeaders").Cells(row, j + 2).Value =
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & "ModeUsed").Cells(speed +
1, 1).Value
.Range("ShipHeaders").Cells(row, j).Interior.ColorIndex = 20
.Range("ShipHeaders").Cells(row, j + 1).Interior.ColorIndex = 20
.Range("ShipHeaders").Cells(row, j + 2).Interior.ColorIndex = 20

burn = burn + CDbl(intervalSize / 60) *
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) &
"BurnRateUsed").Cells(speed + 1, 1).Value 'burn fuel during transit
```

```
dist = dist + ship.drillFP(1)
pimDist = pimDist + averageSpeed * intervalSize / 60
time = DateAdd("n," intervalSize, time)

'until 2nd drill
ElseIf i >= ship.drillStarts(1) + ship.drillDurations(1) And i < ship.drillStarts(2) Then
'rush to front of window
If dist + ((ship.RushSpeed + oceanSpeed) * intervalSize / 60) <= pimDist + 4 * averageSpeed Then
speed = ship.RushSpeed
'hold pim speed
Else
speed = Application.WorksheetFunction.RoundDown(averageSpeed, 0) - oceanSpeed
End If
.Range("ShipHeaders").Cells(row, j).Value = speed
.Range("ShipHeaders").Cells(row, j + 1).Value = dist
.Range("ShipHeaders").Cells(row, j + 2).Value =
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & "ModeUsed").Cells(speed +
1, 1).Value


burn = burn + CDbl(intervalSize / 60) *
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) &
"BurnRateUsed").Cells(speed + 1, 1).Value 'burn fuel during transit
dist = dist + (speed + oceanSpeed) * intervalSize / 60
pimDist = pimDist + averageSpeed * intervalSize / 60
time = DateAdd("n," intervalSize, time)


'do drill 2
ElseIf i >= ship.drillStarts(2) And i < ship.drillStarts(2) + ship.drillDurations(2) Then
speed = ship.drillSpeeds(2)
.Range("ShipHeaders").Cells(row, j).Value = speed
.Range("ShipHeaders").Cells(row, j + 1).Value = dist
.Range("ShipHeaders").Cells(row, j + 2).Value =
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & "ModeUsed").Cells(speed +
1, 1).Value
.Range("ShipHeaders").Cells(row, j).Interior.ColorIndex = 20
.Range("ShipHeaders").Cells(row, j + 1).Interior.ColorIndex = 20
.Range("ShipHeaders").Cells(row, j + 2).Interior.ColorIndex = 20

burn = burn + CDbl(intervalSize / 60) *
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) &
"BurnRateUsed").Cells(speed + 1, 1).Value 'burn fuel during transit
dist = dist + ship.drillFP(2)
pimDist = pimDist + averageSpeed * intervalSize / 60
time = DateAdd("n," intervalSize, time)

'until destination
Else
'rush to front of window
If dist + 4 * averageSpeed <= targetDistance + ship.finalOffset Then
If dist + ((ship.RushSpeed + oceanSpeed) * intervalSize / 60) <= pimDist + 4 * averageSpeed Then
speed = ship.RushSpeed
Else
speed = Application.WorksheetFunction.RoundDown(averageSpeed, 0)
```

```
End If
‘hold pim speed
Else
‘speed = Application.WorksheetFunction.RoundDown(averageSpeed, 0) - oceanSpeed

speed = Application.WorksheetFunction.RoundUp((targetDistance - dist + ship.finalOffset) /
((intervalCount - i) * intervalSize / 60), 0)
End If
.Range(“ShipHeaders”).Cells(row, j).Value = speed
.Range(“ShipHeaders”).Cells(row, j + 1).Value = dist
.Range(“ShipHeaders”).Cells(row, j + 2).Value =
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & “ModeUsed”).Cells(speed +
1, 1).Value


burn = burn + CDbl(intervalSize / 60) *
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) &
“BurnRateUsed”).Cells(speed + 1, 1).Value ‘burn fuel during transit
dist = dist + (speed + oceanSpeed) * intervalSize / 60
pimDist = pimDist + averageSpeed * intervalSize / 60
time = DateAdd(“n,” intervalSize, time)

End If

If speed <> ship.lastSpeed Then
.Range(“ShipHeaders”).Cells(row, j).Interior.ColorIndex = 27
.Range(“ShipHeaders”).Cells(row, j + 1).Interior.ColorIndex = 27
.Range(“ShipHeaders”).Cells(row, j + 2).Interior.ColorIndex = 27
If modeAtSpeed(ship, speed) <> modeAtSpeed(ship, ship.lastSpeed) Then
.Range(“ShipHeaders”).Cells(row, j).Interior.ColorIndex = 45
.Range(“ShipHeaders”).Cells(row, j + 1).Interior.ColorIndex = 45
.Range(“ShipHeaders”).Cells(row, j + 2).Interior.ColorIndex = 45
End If
End If
ship.lastSpeed = speed
‘exit condition
If dist >= targetDistance + ship.finalOffset Then
Exit For
End If
Next i
bShips(ship.index).fuelBurnedOld = burn
End With
End Sub



Function getMaxSpeed(ship As battleShip) As Integer
Dim s As String
s = ship.shipType
getMaxSpeed = Application.max(ThisWorkbook.Sheets(UCase(s)).Range(LCase(s) & “ModeMaxSpeed”))
End Function

Function checkSpread(ByRef ship As battleShip, speed As Integer, intervals As Integer) As Boolean
i = ship.index
Dim tempDist As Double
```

```
tempDist = ship.distance + speed * intervalSize / 60
Dim predictedSpread As Double
Dim maxPredictedSpread As Double
‘check against ships that have already set their speeds for this interval
For j = 0 To i - 1
If bShips(j).countInSpread = True Then
predictedSpread = (ship.distance - bShips(j).distance) + CDbl((intervals) * intervalSize / 60) * CDbl(speed
- currentSpeeds(j)) ‘+ speed * intervalSize / 60
If (Application.WorksheetFunction.max(predictedSpread, -predictedSpread)) > maxSpreadAllowed And
ship.countInSpread = True Then ‘And currentInterval <> 0 Then
checkSpread = False
Exit Function
End If
End If
Next j
‘check against ships that still have to set speed (assume their speed = their lastSpeed)
For j = i + 1 To UBound(bShips)
If bShips(j).countInSpread = True Then
If currentInterval <> 0 Then
predictedSpread = (ship.distance - bShips(j).distance) + CDbl(intervals * intervalSize / 60) * CDbl(speed -
bShips(j).lastSpeed)
Else
predictedSpread = (ship.distance - bShips(j).distance) + CDbl(intervals * intervalSize / 60) * CDbl(speed -
getAssumedStartSpeed(bShips(j)))
End If
If (Application.WorksheetFunction.max(predictedSpread, -predictedSpread)) > maxSpreadAllowed And
ship.countInSpread = True Then ‘And currentInterval <> 0
checkSpread = False
Exit Function
End If
End If
Next j
checkSpread = True
End Function
Sub checkSpreadAfterDrills(ByRef ship As battleShip)
i = ship.index
Dim maxSpreadNow As Double
Dim sprd As Double
For j = 0 To i - 1
sprd = ship.distance - bShips(j).distance ‘- (ship.lastSpeed - bShips(j).lastSpeed) * intervalSize / 60
maxSpreadNow = Application.WorksheetFunction.max(maxSpreadNow, sprd, -sprd)
Next j
For j = i + 1 To UBound(bShips)
sprd = ship.distance - bShips(j).distance ‘- (ship.lastSpeed - bShips(j).lastSpeed) * intervalSize / 60
maxSpreadNow = Application.WorksheetFunction.max(maxSpreadNow, sprd, -sprd)
Next j
If maxSpreadNow < maxSpreadAllowed And ship.countInSpread = False Then
bShips(i).countInSpread = True
ship.countInSpread = True
If Sheets(“Short Term Planner”).RushAfterDrillsButton.Value = True Then
bShips(i).needNewSpeeds = True
ship.needNewSpeeds = True
bShips(i).rushing = False
ship.rushing = False
ship.countInSpread = True
```

```
bShips(i).countInSpread = True
End If
Else
If Sheets("Short Term Planner").RushAfterDrillsButton.Value = True Then
ship.rushing = True
bShips(i).rushing = True
End If
End If
End Sub
Function getAssumedStartSpeed(ship As battleShip) As Integer
getAssumedStartSpeed = 0
For i = 40 To 0 Step -1
If ship.speedIntervals(i) <> 0 Then
getAssumedStartSpeed = i
Exit For
End If
Next i
End Function

Sub recordFuelSaved()
fuel = 0
For s = 0 To UBound(bShips)
fuel = fuel + bShips(s).fuelBurnedOld - bShips(s).fuelBurned
Next s
ThisWorkbook.Sheets("Short Term Schedule").Range("ScheduleFuelSaved").Value = fuel
End Sub
```

LIST OF REFERENCES

Brown G, Kline J, Rosenthal R, and Washburn AR (2007) Steaming on convex hulls, *Interfaces*, 37:342–352.

Brown G, Kline J, Rosenthal R, and Washburn A (2011) Mixed mode fuel minimization, U.S. Patent 8,050,849, November 1.

Crawford, DK (2014) Alternative practices to improve surface fleet fuel efficiency. Master's thesis, Naval Postgraduate School, Monterey, CA.

DeGrange W (2012) Why Won't You Use My Model? Difficulties in Implementing Optimal Scheduling Models, *New Horizons: The Role of Operations Research in Planning DOD's Future, 3RD Annual Military Applications Society Conf.* (Monterey, CA), March 27–28.

DODLIVE (2015, January 25). U.S. Navy Energy, Environment and Climate Change, http://greenfleet.DODlive.mil/energy-conservation-measures-ecms/.

U.S. Navy (2014) CNO's Position Report: 2014. Accessed 25 January 2016, www.navy.mil/cno/docs/141104_PositionReport.pdf.

Fonte S (2009) "A cost estimation analysis of U.S. Navy ship fuel-saving techniques and technologies." MS Thesis, Naval Postgraduate School Monterey, California.

Friedman N (2014) *Fighting the Great War at Sea, Strategy, Tactics and Technology* (Seaforth Publishing, Barnsley, Great Britain).

GAO-14-749 (2014) Government Accountability Office Report to Congressional Committees, Littoral Combat Ship July.

McCoy M (2012) NAVSEA Reducing Fleet Energy Consumption *Currents* (U.S. Navy, Chief of Naval Operations Energy and Environmental Readiness Division) Summer edition.

NAVDORM (2012) COMNAVSURFOR/COMNAVAIRFOR Instruction 3530.4 Ch. 2.

Naylor B (2015) "CVN Speed of advance" Project Report, Naval Postgraduate School Monterey, CA.

Pehlivan H (2015) Email message to the author. June 19. Fuel consumption rates for CG1, CG2, DDG1, DDG2, LHA, LHD, LPD, LSD, LCS1, LCS2.

Richards M (2015) Email message to the author, September 11. Transit data from USS Sampson summer 2014.

Schrady D, Smyth G, Vassian R (1996) Predicting Ship Fuel Consumption: Update, MS Thesis, Naval Postgraduate School Monterey, CA.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California